FOG SEQUENCES ON THE CENTRAL CALIFORNIA COAST WITH EXAMPLES.

Craig Allen Peterson

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by

Craig Allen Peterson

September 1975

Thesis Advisor: D.F. Leipper

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This study uses a synoptic approach, focusing on sequences

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Results show that, although the model is general in nature, a correlation between the stages of the model and observed fog exists. The relationship of the time of occurrence of dense fog and the trends in the height of the inversion base and daily maximum temperatures at the top of the inversion and the inland valley are pointed out.

FOG SEQUENCES ON THE CENTRAL CALIFORNIA COAST
WITH EXAMPLES

by

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Lieutenant, United States Navy
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TABLE OF SYMBOLS AND ABBREVIATIONS

C	Degrees Celsius
ft.	foot
Fig.	Figure
G/KG	Grams/Kilograms
GMT	Greenwich Mean Time
HT	Height
I.H.	Inversion Height
M	Meters
NAS	Naval Air Station
NOAA	National Oceanic and Atmospheric Administration
NPS	Naval Postgraduate School
NM	Nautical Miles
PST	Pacific Standard Time
Raob	Radiosonde Observation
RH	Relative Humidity
SAT	Sea Air Temperature
SST	Sea-Surface Temperature
SRVIS	Scanning Radiometer Daytime Visual
T	Temperature
Z	Zulu Time
$>$	Greater than
$<$	Less than
Δ	Difference

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I. INTRODUCTION AND APPROACH

Marine fog along the West Coast of the United States is a phenomenon which affects the day-to-day lives and activities of both the ocean operators and the coastal inhabitants. When dense fog occurs, that is, when suspended water particles reduce horizontal visibility at the earth's surface to 1000 meters (5/8 mile) or less, (Petterssen 1958), its impact is felt by both the military and commercial communities. There are real dollar and cents losses through the suspension of operations and there are risks of accidents from continued operations in an area of reduced visibility.

Marine fog along the California coast is a product of the great contrast between the thermal characteristics of the ocean and of the land, and the modification of the general atmospheric circulation by the topographical features of the land. AWSM 105-44 (1954) describes a large portion of the marine fog as coastal high inversion fog. As defined here this refers to stratus which has formed over a cold coastal current and moved inland. The season of highest frequency for these fogs in California extends from spring through summer into early fall, the area affected extends from northern Oregon well into lower California, with maximum frequency between Pt. Reyes and Pt. Arguella.

Misciasci (1974) states that three main approaches have been taken in the analysis and forecasting of California

coastal fog: climatoglogical, statistical-numerical, and synoptic. Most approaches to forecasting have considered only point locations where the data are available, without an attempt to draw relationships for the coast as a whole. In this paper a synoptic approach will be used, focusing upon the non-diurnal aspects of coastal fog. A development model will be utilized in order to delineate patterns of the fog phenomenon along the California coast. Periods of time related to a given fog situation will be selected and the development model tested to determine its applicability to actually observed fog conditions. Individual non-diurnal indices will be considered to determine if day-to-day changes represent trends which can be used to refine the development model and aid the forecaster. An actually observed fog development sequence will be presented and related to the development model.

II. BACKGROUND

The use of a synoptic approach and the advantages of determining a day-to-day sequence based on the non-diurnal aspects for investigating fog were alluded to by Taylor (1917) in his paper, "The Formation of Fog and Mist." In this paper a forecast for a non-fog situation is made by a fellow investigator which "shows clearly that the question of whether or not fog is likely to form in the course of the night does not depend only on the atmospheric conditions at the time of the forecast or the general conditions forecasted for the night. It depends also, to a large extent, on the sequence of weather for some days previous to the time of the forecast." Although this concept was clearly stated in 1917, only parts of such sequence have been defined and discussed. Although certain components have been put into a definable form, few successful attempts have been made to fit the components together into a sequence of steps or stages covering not only a specific locality but also a large area over a period of days. One notable exception focusing attention on a localized area is Leipper's (1948) "Fog Development at San Diego," in which the fog situation is developed in a systematic manner. Specific occurrences of fog were shown to result from the effect of local influences upon a given set of initial conditions. It should be noted that this fog

development sequence applied to winter-time situations in the three years (1943 to 1945) studied. It pertained to surface and not "high inversion" fog.

In Leipper's (1968) paper, "The Sharp Smog Bank and California Fog Development," it was observed that certain stages of fog situations described in his 1948 paper were similar to conditions described by Edinger (1963) in the summer of 1961 farther north in the Los Angeles area and to those which Stephens (1965) reported for the sharp smog bank.

Instruction for the extension of Leipper's 1948 fog development model to the other seasons as well as its use in the winter appears frequently in the forecaster handbooks used in the San Diego area. NAS Imperial Beach, NAS North Island, and NAS Mirmar use objective fog forecast procedures prescribed by Fleet Weather Facility, San Diego, California. The latter mentioned section of the manual presents the four stages of Leipper's 1948 fog development model and the method using indices for fog forecasting presented in the same work. Table 1 is a worksheet taken from NWS, "Local Areas Forecaster's Handbook" FWF San Diego, California for objectively forecasting fog based on Leipper's indices.

For coastal areas north of San Diego, there is a minimum of objective methods or developmental models (as Leipper's) for forecasting fog. Some of the existent approaches are described below.

The Air Weather Service Manual 105-44 gives ten parameters which have been found generally to be important in studies of

TABLE 1

Objective Method For Forecasting Fog

1) PARAMETERS

a) Base of inversion on 12GMT sounding (SAN)		______ FT
b) Highest air temperature above base of inversion (SAN)	Ta=	______ C
c) Sea temp at 0800LST on preceding day (Scripps)	Tw=	______ C
d) Dew point temp at 1630LST on preceding (NZY)	TD_p1630=	______ C
e) Mixing ratio at 10,000' on the 12GMT SAN sounding	MR=	______ g/kg

2) INDICES

	FAVORABLE	UNFAVORABLE
a) Base of inversion= ______ FT	Below 1300'	Above 1300'
b) Ta minum Tw = ______ C	Above 0 C	Below 0 C
c) TD_p1630 minum Tw= ______ C	Above -5 C	Below -5 C
d) MR at 10,000' = ______ g/kg	Less than 3.5 g/kg	More than 3.5 g/kg

NOTE: All must be favorable or forecast to become favorable to indicate fog formation.

3) Forecast anf Verification

a) Forecast valid for period 1800-0600 LST following time of observation used in computations.

b) Verification (circle one)

Visibility	Above 2 miles		Below 2 miles	
Obstruction to vision	Fog	Ground Fog	Haze	None

COMPUTED BY: ____________________

DATE: ___________________________

California high inversion coastal fog. Of the ten parameters, several have to do with diurnal variations after the fog or stratus has formed at sea, which affects its movement on shore. Parameters which have non-diurnal aspects (e.g. height of the inversion, maximum afternoon temperatures at the coast, afternoon dew-point depression and strength of onshore wind components) are not unlike the Leipper's (1948) indices.

Point Mugu's Forecaster's Handbook describes the synoptic situation associated with the onset of stratus and accompanying fog and haze in the period April to October. The handbook establishes conditions which are very similar to a combination of Stages 1 and 2 of Leipper's model (Rosenthal 1972). The position of the North Pacific high, the inversion, the orientation of isobars and thermal troughs and sea-surface temperatures are taken into account. A synoptic weather pattern, including the thermal trough over the inland California valleys and a strong, persistent North Pacific high off the west coast, results in isobars parallel to the coast in northern and central California. Such an orientation was observed frequently to accompany the occurrence of fog and stratus. The North Pacific high is credited with producing subsidence of warm dry air which restricts the marine air to within the lowest thousand feet above the surface. A pronounced temperature inversion thus exists between the cool, moist marine air and the subsiding warm dry air above. The determination of the true role of the sea-surface temperature

in the formation process was described as difficult. The thumb rules and forecasting aids on stratus and fog for the above conditions and the conditions after the occurrence of the formation processes were general in nature. The manual as a whole, however, allows for the possibility that a general sequence might be occurring in the formation of fog.

The U. S. Naval Fleet Numerical Weather Center (FNWC) in Monterey, California, provides an objective fog forecast based on a computerized statistical analysis of various parameters which are either products of numerical analyses or primitive equation prognoses. These parameters consist of air temperature, evaporation, condensation, relative humidity, geostrophic thermal advection, and horizontal mixing. The primary use of this product is in the Optimum Ship Tracking Routing (OTSR) program provided by FNWC to Naval and government contract shipping. (Misciasci 1974). According to Renard (1974) use of this product is limited and the accuracy is not believed to be at an operationally acceptable level.

The forecaster's manual for NAF Monterey contains no objective method for forecasting fog. Fericks (1952) and Read (1957) attempted to set up a fog forecasting technique for Monterey using the indices method of the San Diego study. Different critical values were used for the indices at Monterey. The 1952 paper found, for a period of May to October, that the occurrence of fog on a day when all indices were favorable was only fair with 56% accuracy.

However, it was found that there was an excellent correspondence to non-fog conditions when the indices were all unfavorable. The 1956 paper, using the same indices, had a wide discrepancy in the results using the same indices although the correspondence of unfavorable indices remained good.

III. DEVELOPMENT MODEL

Based upon the previously cited studies of west coast marine fog and observations of fog development in the Monterey, California area, it was felt that a sequence which fits the fog formation situation for a large segment of the coast could be developed, along the same lines as Leipper's (1948) model, but using a somewhat different set of conditions. This sequence would be for fog situations within the period which extends from spring through summer into early fall. The sequence, though made up of numerous individual phases which interact with each other, would be considered as comprising three distinct stages.

A. STAGE I

The initial conditions for fog development consists of a strong low surface inversion to restrict the vertical movement of moisture and thus to cause a thin lower layer of air to approach saturation (Leipper 1948). This initial condition for the northern and central California coast may be brought about when the eastern North Pacific subtropical high is well established and is positioned in such a manner that the isobaric pattern is generally parallel to the coast with the eastern edge of the high extending inland toward the north. With the high positioned in the above manner, a strong northwest flow would prevail over most of the southern coast.

Blake (1948) pointed out that large scale subsidence could be associated with the subtropical North Pacific and North American cyclones in the summer months. This subsidence could possibly produce a strong inversion at or near the surface depending on the characteristics of the underlying surface.

The effect of the temperature of the sea surface that the air passes over in its southward movement must be taken into account even in this stage of the development. A marked difference is seen between the orientation of sea isotherms that the air passes over at sea and those along the coast. Isotherms at sea are oriented almost east-west with increasing temperature toward the south. Along the coast the orientation becomes effectively north-south with temperature decreasing toward the coast. Therefore, the surface air flow in its movement southward is being affected differently at sea, along the coast, and over land. This in turn affects the height of the inversion. During this stage in the presence of subsidence, dry clear weather should be characteristic of the inland valleys. The surface marine air along the coast at this time would be expected to be cool and low in moisture content due to the sea-surface isotherm pattern it is moving over. This would form a low inversion under the warm dry air aloft. A surface air temperature higher than that of the sea surface should be observed. The marine air farther at sea moving over the east-west oriented isotherms would be expected to be warmed

from below and to produce a near adiabatic lapse rate in the lower levels. The moisture content would be expected to be greater than that of the shoreward air due to evaporation from the warmer sea surface. This moist layer could be expected to extend up to the subsidence inversion.

Care must be taken in evaluating the sea-surface temperature pattern during this stage of the development. Figure 1 shows sea-surface temperatures for four different summer months, three in 1974 and one in 1975. The variance in the orientation of the isobars is obvious. There is also a definite year-to-year variation in the values of sea-surface temperature. If available, the sea-surface pattern, for the specific time and area under consideration, should be used to determine the manner in which the new air-mass structure (that results during this Stage) will be initially affected. In the summary, the conditions which are characteristic of only Stage I are indicated by an asterisk (*). Summarizing, conditions which should be observed during Stage I are:

*1) The eastern North Pacific subtropical high should be well established off the coast with the isobars parallel to the southern coast and the eastern edge of the high extending inland farther north.

2) Subsidence should be taking place along the coast and inland.

*3) The inversion should be near or at the surface.

4) A strong northwest flow should be observed offshore.

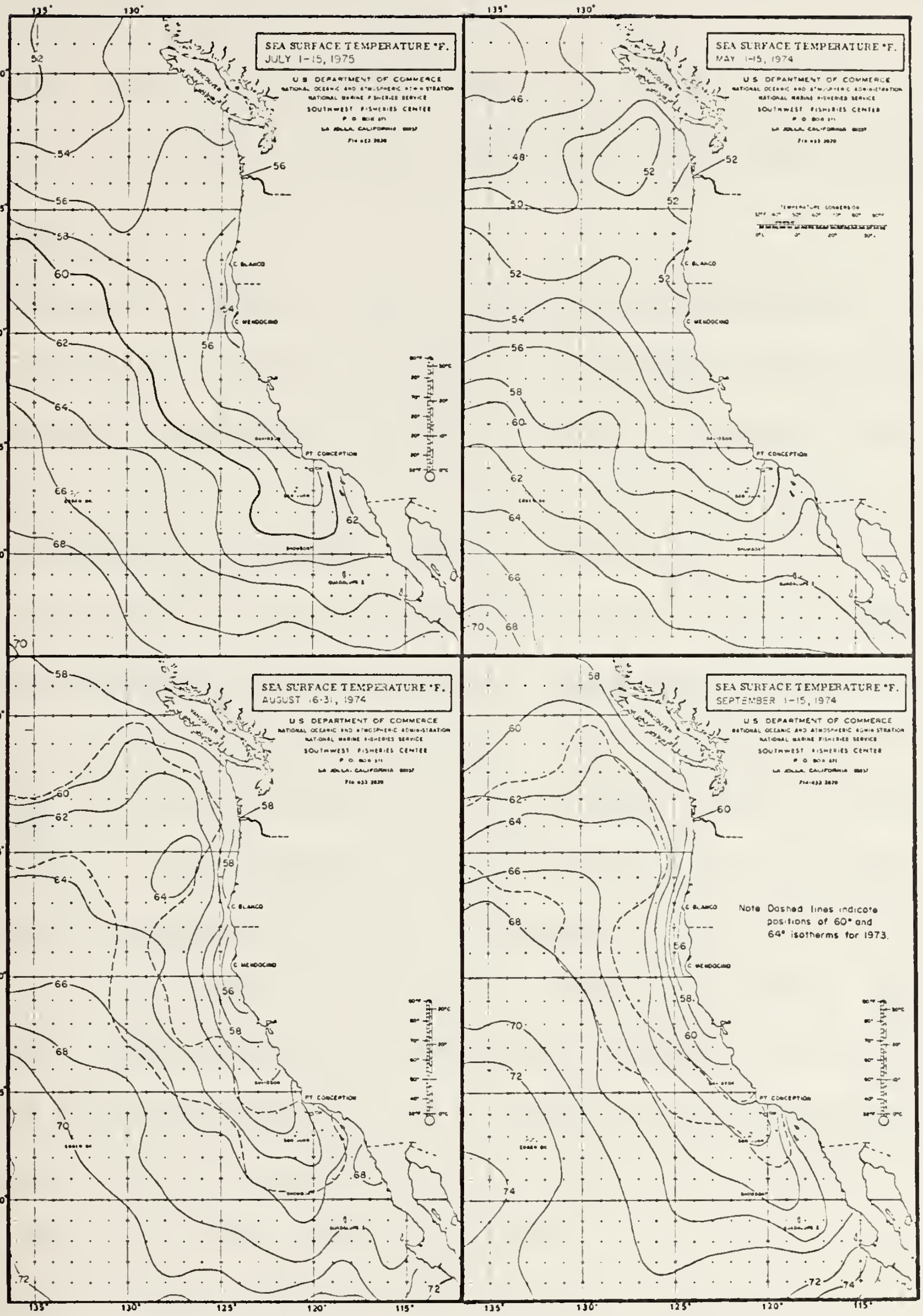


Fig. 1. Sea Surface Temperature Patterns, West Coast of the United States. 15-day averages for 1-15 July 1975, 16-31 May 1974, 16-31 August 1974, 1-15 September 1974.

*5) Clear warm air off the coast and extending seaward should be observable with the surface air temperature warmer than the sea-surface temperature.

6) Coastal visibility should be good.

7) The inland valleys should be clear night and day.

B. STAGE II

During the second stage of the fog development, the high would protrude farther inland over extreme north California, Oregon, and Washington with the isobaric pattern remaining oriented parallel to the majority of the California coast. This frequently observed isobar orientation is the result of the interaction of the north Pacific high and the heat induced thermal trough generally found in the California inland valleys (Rosenthal 1972). The increase in strength and the northward movement of the trough could be thought of as a result of conditions set up and observed in Stage I. It would be expected that a noticeable increase in termperature would be observed at inland valley stations. When heating is most intense, the thermal trough is best established and most effective in strengthening the onshore surface pressure gradient and in causing the isobars to parallel the coast (Rosenthal 1972).

At the coast, surface winds tend to acquire an easterly component. Warmer air from the land would then be observed to flow over the coastal ocean area. This air is also initially warmer than the sea surface and the inversion is strengthened by surface cooling. The heat content of this

layer decreases due to conduction of heat downward (Sverdrup 1942). A lifting of the surface inversion base with an increase in the air temperature at the top of the inversion should be observed. Haze may be observed at sea at this point. Further radiative cooling from the top of the lifted layer and additional mixing causes increased saturation and condensation with a consequent thickening of the marine layer between zero and 100 meters. The lowest air layers become nearly saturated at a temperature close to that of the underlying sea surface. After fog is formed, a surface air temperature, several degress lower than the sea-surface temperature should be observed.

Due to the wind flow, the orientation of the isobars, the intensification and positioning of the thermal low, and the sea surface temperature structure, the conditions in Stage II could be met first along the southern portions of the coast. A wedge like movement of fog development up the coast might develop as the conditions in Stage II are met. In the summary, the conditions which are characteristic of only Stage II are indicated by an asterisk (*).

Summarizing, the conditions which should be observed during Stage II are:

*1) The eastern North Pacific subtropical high should be seen to push farther inland in the north with the general isobaric pattern remaining parallel to the southern coast in California.

*2) The thermal trough should tend to become more intense and extend further north into the California inland valleys.

*3) Temperatures in the inland valleys should show an increase.

4) The inland valleys should be clear.

*5) The inversion height over the coastal ocean area should be an effective measure of the marine layer and the phase reached in the sequence during Stage II. An increase in height from zero to 100 meters should be seen in Stage II.

6) A decrease in surface air temperature should be observed as the inversion height rises, bringing the surface air temperature closer to the sea-surface temperature.

7) Haze may be observed at sea.

8) The winds veer to east of north along the coast, lowering in intensity.

9) The development of a wedge of fog along the coast of southern California should be observable.

C. STAGE III

In the third stage of the fog development, the surface winds have diminished along the coast with the northwesterly airflow remaining at sea. This condition allows the sea breeze to again become effective. With favorable conditions for an onshore flow, the moist marine layer moves toward shore over the increasingly colder sea surface isotherms. The formation of fog over larger areas of the sea surface should be observed during this period. Leipper states that radiation cooling causes first a decrease in temperature after fog is formed and then an increase evaporation. Both of these effects markedly intensify fog and serve to maintain it (Leipper 1948).

Coastal sites will still be reporting clear skies. Surface observation may show an increase in reports of haze. The coastal raobs will show an increase in the height of the inversion base. When the inversion height is from zero to 100 meters as shown by the coastal raobs, fog development should already be taking place at sea. Bay fogs probably would be observed first during this stage, due to the protected nature of the air from the offshore circulation and the increased effect of sea breeze in this area.

The first day that the marine layer approaches the coast rapid dissipation with daytime heating over land would be expected. The inversion height on succeeding days should be seen to rise to the 100-to 300-meter level, with an increase in the temperature at the top of the inversion. This rise in inversion height is a consequence of the thickening of the fog layer at sea, which may now be present both day and night, and the decreased ability of conditions onshore to dissipate the thickened invading moist marine layer. The fog bank at sea may be observed to protrude into the coastal valley in late afternoon. With nighttime cooling of the moist air over the land, fog is formed. The relative humidity taken at an elevated inland site should give a good indication of the extent to which the marine air has moved inland.

On successive days the marine layer below the inversion should continue to deepen, and extend farther inland. Coastal sites should observe fog lasting longer and penetrating

farther inland. As the inversion height approaches the 400-meter level thick fog at the surface may no longer be observed, with light fog being observed almost continually. When the inversion height exceeds the 400-meter level, low stratus should be observed along the coast with no reports of clear skies during the day. Drizzle may occur when the inversion is at or near 400 meters and ceilings are reported in the 100- to 300-foot range. This is considered the end of the sequence although earlier conditions of Stage II may be resumed if the inversion height lowers again, for some reason, below the 400-meter level. In the summary, the conditions which are characteristic of only Stage III are indicated by an asterisk (*).

Summarizing, conditions which should be observed during Stage III are:

1) Surface winds should be observed to diminish along the coast with the sea breeze becoming effective.

2) Fog should be observed first in bays and over the colder sea-surface isotherms in the afternoon.

3) After fog formation a surface air temperature several degrees lower than the sea surface temperature may be observed in fog at the coast.

4) Haze may be reported at coastal sites.

5) The inversion height should show an increasing trend along with the maximum temperature at the top of the inversion.

*6) Fog should be observed over the coast with an inversion height from 100- to 300-meters and extend farther inland as the sequence proceeds.

*7) The relative humidity taken at an inland site should give an indication of the extent to which the marine air has penetrated.

*8) Drizzle may occur as the inversion approaches 400 meters.

*9) When the inversion height exceeds 400 meters, stratus without fog should be observed.

IV. PRESENTATION AND INTERPRETATION OF DATA

The full demonstration of the day-by-day sequence of fog development would require adequate data covering an extensive coastal area over an extended period of time. The data would have to be organized in such a manner that they revealed how the principle processes interacted in each of the three stages of the development model. However, as Austin (1974) points out, there is a difficult observation problem in describing a large-scale synoptic situation related to fog.

For the purpose of this study data have been gathered from various sources, both published and unpublished, for three separate fog-related periods. Table 2 gives the time frames, surface observation sites, and data types as well as data sources available for each period.

The prime factor for selection of time frame and area for Period A was the availability of oceanographic data from the Calspan Report, "Marine Fog Studies Off the California Coast" (Mack 1975), and the logs of the Naval Postgraduate School's oceanographic research vessel, ACANIA, used in those studies.

Fog development sequences at Monterey were watched by the author and his adviser during the summer of 1975. Period B was chosen on the basis of the initiating conditions of Stage I being observed. Another consideration for selection

TABLE 2

Period	Time Frame	Surface Observation Sites	Data Available	Sources
A	18 Aug - 5 Sept 1974	NAS North Island PMR Pt. Mugu Pt. Pinos Monterey Santa Cruz NAS Moffett Field S.E. Farrallon Island Bodega Bay R/V Acania	1. Surface Observations 2. RAOBS (Oakland, Monterey, Pt. Mugu, R/V Acania) 3. Maximum Temperatures 4. Satellite Photographs 5. Sea-Surface Temperature 6. Relative Humidity Hidden Hills, Salinas, Calif. 7. Synoptic Surface Weather Pattern 8. Ship Reports	1a NWSD Asheville, N.C. 1b NPS Meteorology File 1c PMR Pt. Mugu 2 Oakland, Monterey, Pt. Mugu, R/V Acania 3 Calif. Climatological Data 4 NOAA II, DMPS 5a Fishing Information S.W. Fisheries Ctr 5b R/V Acania Log 6 Dr. D. Leipper 7 NPS Meteorology file
B	24 Jun - 14 Jul 1975	Monterey R/V Acania	1. Surface Observations 2. RAOBS (Oakland; R/V Acania) 3. Maximum Temperatures 4. Satellite Photographs 5. Sea-Surface Temperature 6. Relative Humidity Hidden Hills 7. Synoptic Surface Weather Pattern	1 Monterey FAA 2 Oakland; R/V Acania 3 NAS Lemoore; N.P.S. 4 GOES 5 R/V Acania 6 Dr. D. Leipper 7 NPS Meteorology Dept.
C	18 May - 15 Sept 1964	Monterey	1. Surface Observations 2. Cloud Tops & Bottoms 3. Maximum Temperatures 4. Synoptic Surface Weather Pattern	1 NAF, Monterey, Calif. 2 Unpublished Paper (Cole 1964) 3 California Climatological Data 4 NPS Meteorology Dept.

of this period was the scheduling of the RV ACANIA for gathering at-sea fog data on 11 July 1975.

Period C was selected because a unique set of data measuring cloud tops and bases was available from an unpublished source (Cole 1964). Period C also spanned the majority of the summer fog period covering the months May through September 1964.

As much data as possible were gathered for each period on the basis of conditions of the development model. Except for the oceanographic data, a large portion of the data gathered would be readily available to forecasters at coastal stations.

A. APPLICABILITY OF DATA TO THE DEVELOPMENT MODEL

Since the data varied for each period and site, there was some concern that the three stages of the development model might not be definable. For each period and site, surface observations were available and these were plotted. (Figure 2 shows the location of each site.) The plots represent time of day versus date. For the purpose of this study a fog-day equals a 24-hour period and begins at 1600 hours the preceeding day and extends to 1559 hours of the date indicated. Surface visibility was represented by shadings with dense fog (visibility less than one-half statute mile) being shown by black, and light fog (visibility one-half to three miles) being shown by connected squares. The general cloudiness case, when fog was not present i.e., haze, overcast, or clear, was shown by light shading,

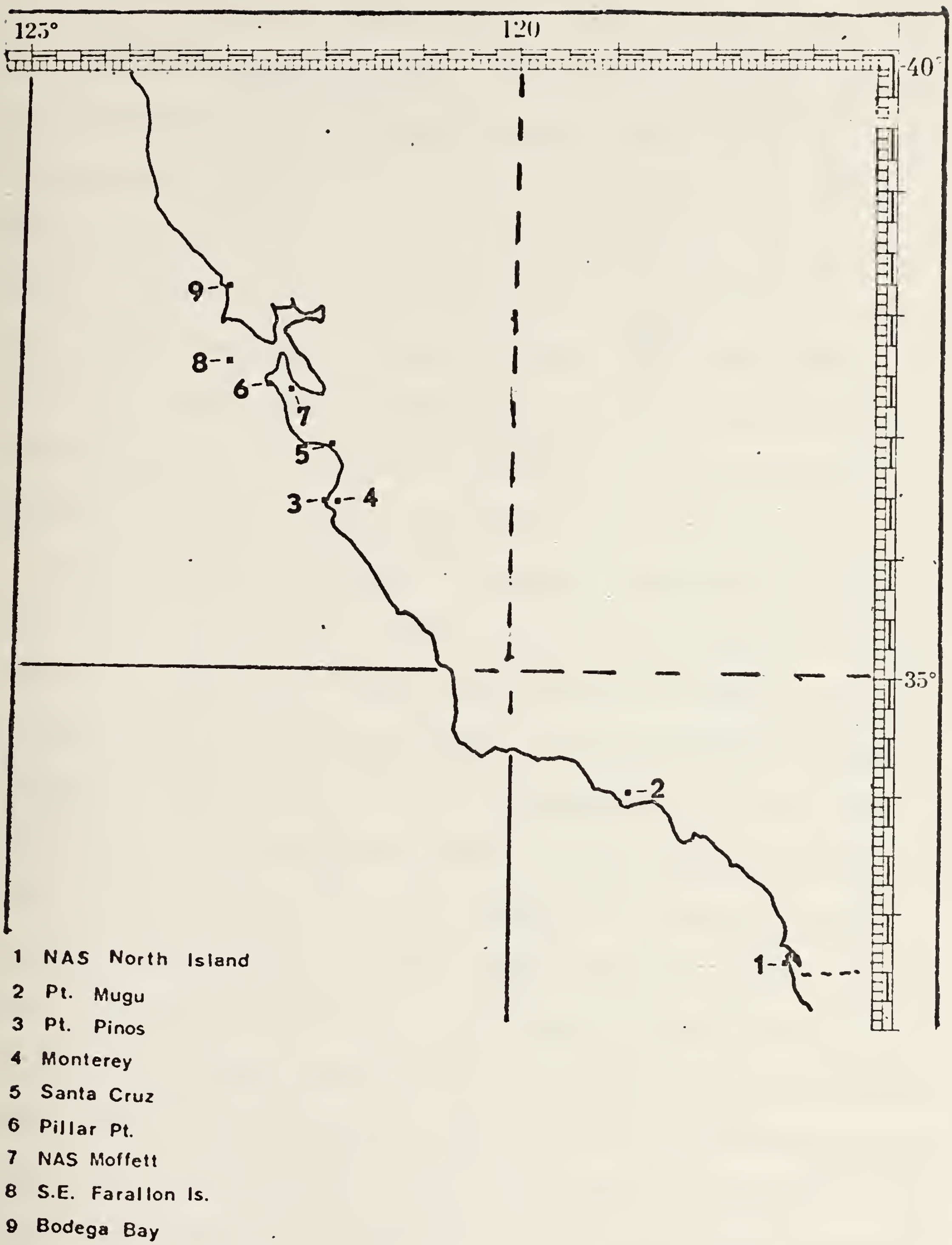


Fig. 2. Position of Coastal Observation Sites

circles, or no shading, respectively. Figures 3, 4, and 5 are the results of these plots. These figures show, for portions of Periods A and B, conditions similar to those expected from the development model, that is, clear days followed by fog days followed by overcast. For Period C there were ten time periods where the same trend was observable. Although several of the ten were affected by fronts, the frontal movement seemed to affect only the speed at which the development sequence took place, an acceleration being apparent. Figures, for Period C, are contained in Appendix A of the master copy of this study.

In an initial attempt to observe any overall sequence in the data, the blocks of days in each period when fog was observed were broken down by site and tabulated against the criteria for the various stages of the development model. Depending upon whether or not a criterion for the model was verified, a yes or no was placed in the appropriate position for each fog block and each criterion. Period C was not considered due to the limited and different nature of the data. Neither a clear cut sequencing of the conditions nor a definite movement from stage to stage of the development model could be determined. This method did determine that dense fog at the coastal sites was primarily observed only after the conditions in Stages I and II had been satisfied.

A daily method was subsequently tried for Periods A and B in an attempt to show a sequence in the conditions and a movement through the stages. Date versus fog stage were

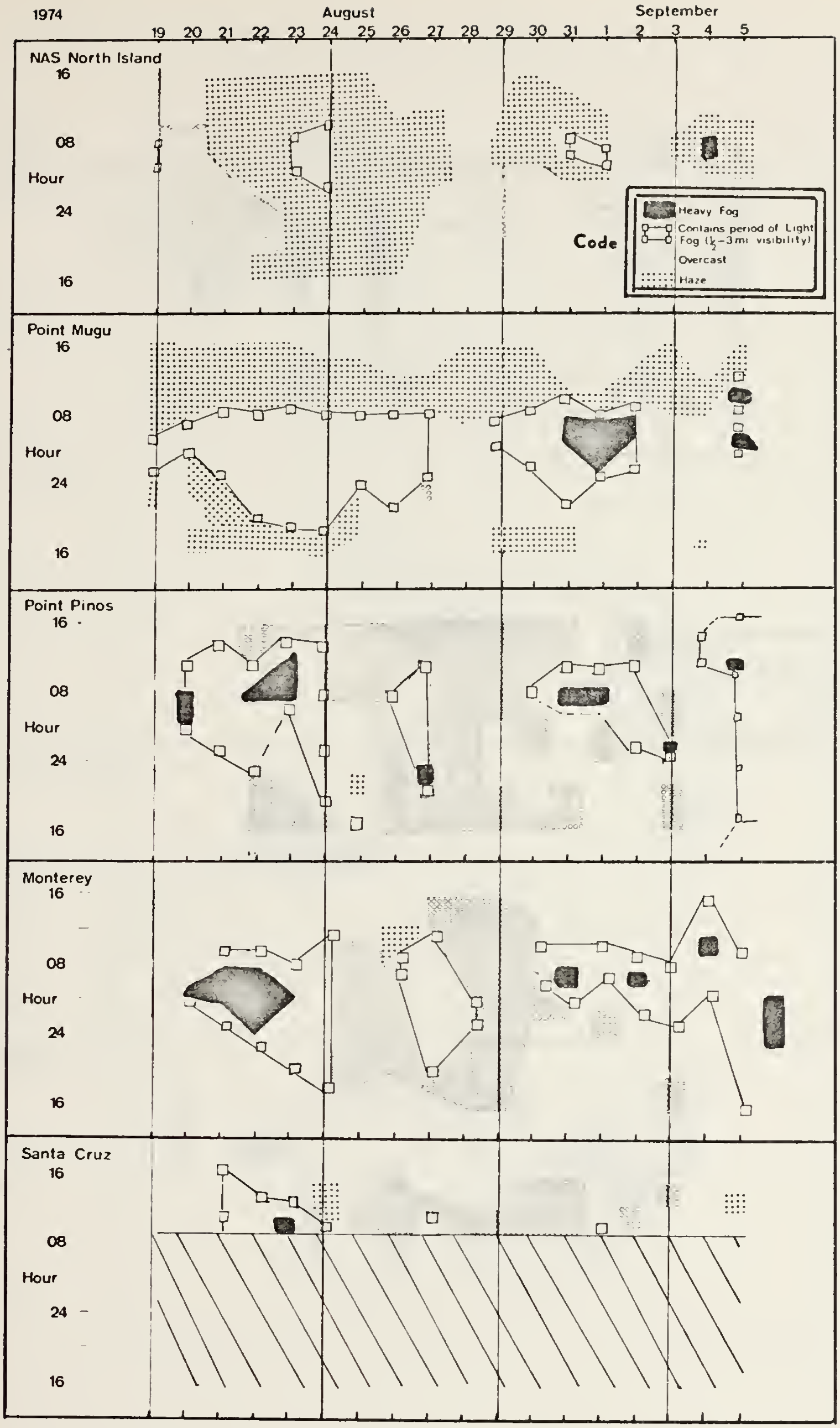


Fig. 3. Hourly Visibility and Cloudiness. Period A.

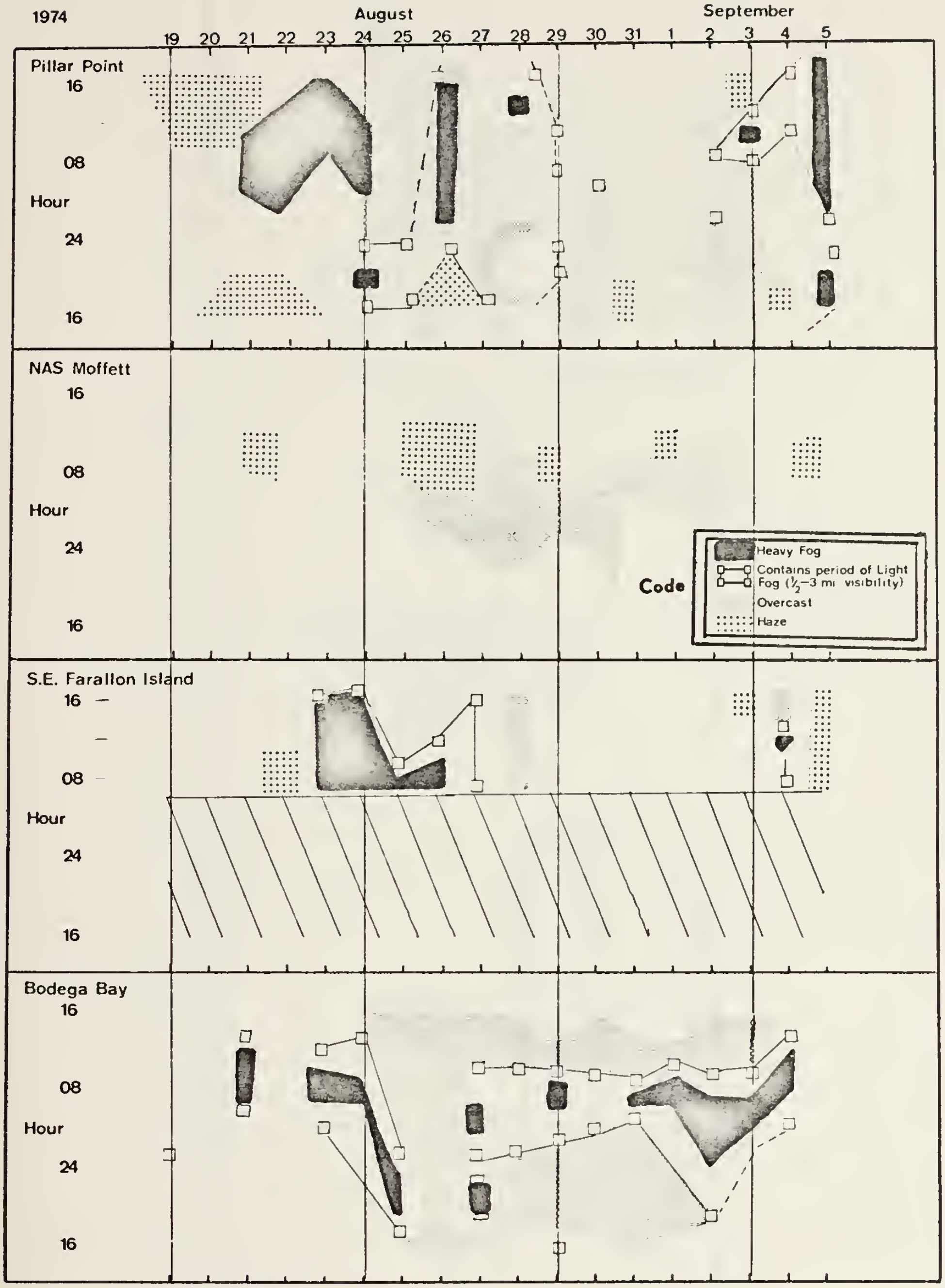


Fig. 4. Hourly Visibility and Cloudiness.
Period A.

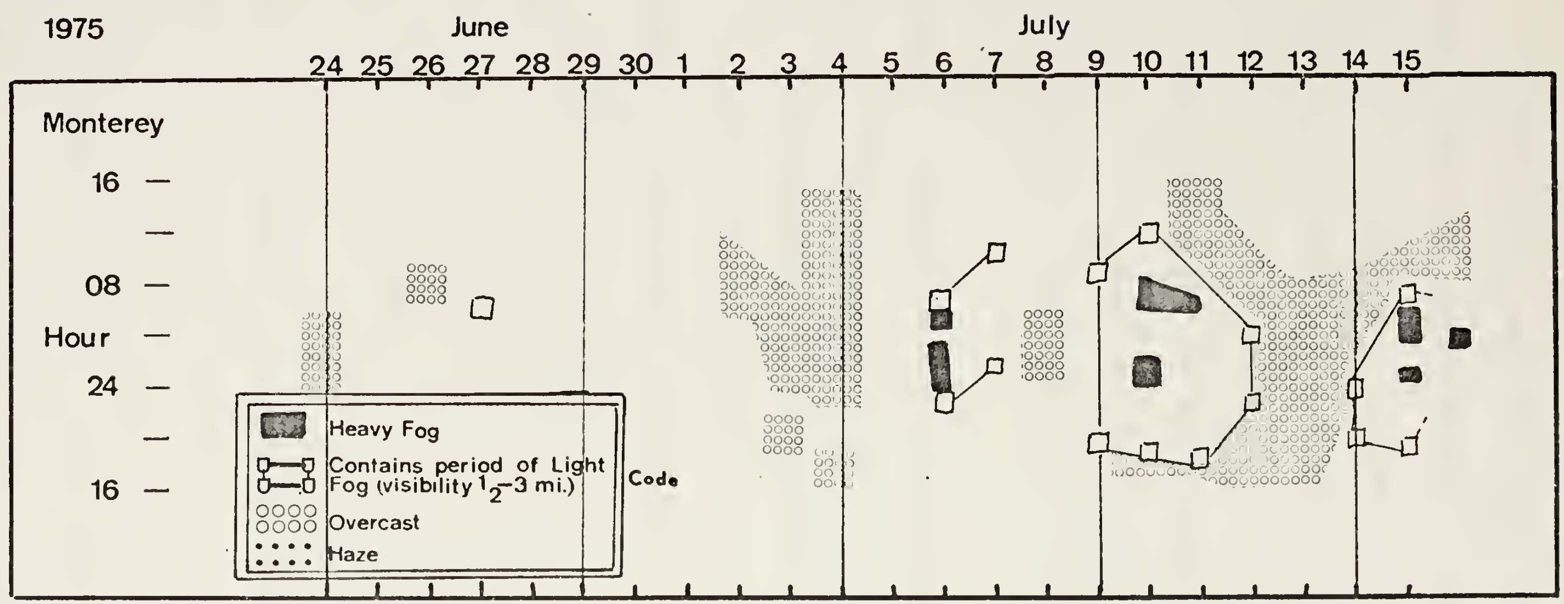


Fig. 5. Hourly Visibility and Cloudiness, Monterey City Airport. Period B.

blocked out in tabular form. The conditions for which the observations matched the model in each stage were counted, and the total number of conditions for each date and stage were entered in the table. An inversion height greater than 400 meters was taken as a negative condition. Graphs were constructed from the tables showing the number of conditions observed each day for each stage and the total number of conditions observed each day. Figures 6 and 7 for Monterey are shown as representative examples of the preceding compilation.

For Period A, several patterns were seen in the graphs which indicate that the conditions in the stages of the development model do determine a fog sequence. In Period A these patterns occur primarily in the first six days where the maximum number of conditions in Stages I, II, and III were observed to succeed each other. Stage I appeared to be in effect only on 19 August 1974 for all the sites except Bodega Bay where it continues until the 20th. The observance of conditions in Stages II and III overlap. The conditions of Stage II built rapidly to a maximum on the 20th at Point Pinos and Monterey, the 22nd at Santa Cruz, Pillar Point, South East Farrallon Island, and the 23rd at Bodega Bay. On successive days a gradual decline in the number of conditions in Stage II was then observed. The conditions of Stage III showed the greatest variance from site to site. This was expected since these conditions depend more heavily on the topography of the land. Stage III became evident on

1974		August													September				
	Conditions	19	20	21	22	23	24	25	26	27	28	29	30	31	1	2	3	4	5
Stage I	1	—																	
	2																		
	3																		
	4	—	—																
	5	—	—	—	—											—			
	6	—																	
	7	—	—	—	—	—	—	—	—	—		—	—	—	—	—	—	—	—
	Total	5	3	2	2	1	1	1	1	1	0	1	1	1	1	2	1	1	1
Stage II	1		—	—	—	—	—			—	—							—	—
	2		—	—		—	—	—		—							—		
	3		—	—	—	—	—							—	—	—	—	—	—
	4	—	—	—	—	—		—	—	—		—		—	—	—	—	—	—
	5		—				—											—	
	6								—										
	7																—		
	8			—	—			—											
	9		—	—	—														
	Total	1	6	5	5	4	4	3	2	3	1	1	0	2	2	2	4	4	3
Stage III	1		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	2	—		—	—	—	—	—			—					—	—	—	—
	3				—	—	—	—											
	4								—	—									
	5			—	—	—	—	—		—			—			—			
	6		—	—	—	—			—						—	—	—	—	—
	7			—		—	—	—	—	—	—								
	8					—								—					
	9						—					—							
	Total	1	2	5	5	6	6	5	4	3	3	2	2	2	2	4	3	3	3
I.H. > 400 M		0	0	0	0	0	0	X	0	X	X	X	X	X	.0	0	0	0	0
Fog observed		Clear	F	F	F	F	LF	Ovc	LF	LF	LF	Ovc	LF	F	LF	F	LF	F	LF

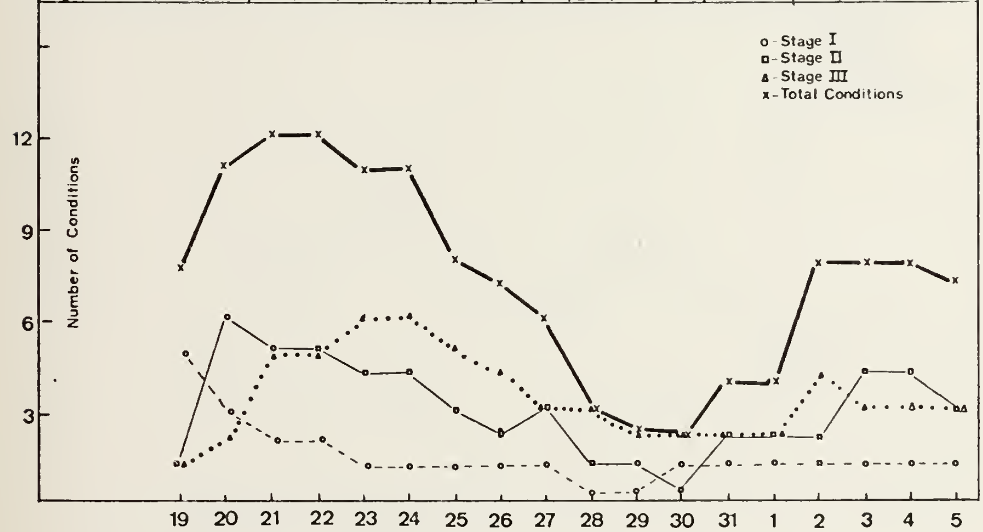


Fig. 6. Conditions for Stages I, II, and III for Monterey City Airport, Period A. In the Tabular section a dash (-) indicates the condition was observed. Inversion Height (I.H.) > 400 meters is indicated by (X). Observed fog is indicated by F (dense fog); LF (light fog); OVC (Overcast).

1975		June							July														
	Conditions	24	25	26	27	28	29	30	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Stage I	1	–						–		–		–	–					–					
	2																						
	3						–						–										
	4	–	–	–				–	–	–	–	–					–	–	–	–			
	5		–	–				–	–	–	–												
	6	–	–	–		–	–	–	–	–	–	–											
	7		–	–	–	–	–	–	–	–	–		–	–	–	–		–	–	–	–	–	–
	Total	3	4	4	1	2	3	5	4	5	4	3	3	1	1	1	1	3	2	2	1	1	1
Stage II	1		–	–	–	–	–	–				–		–		–	–	–		–			
	2																						
	3		–	–	–	–					–	–	–	–	–	–	–	–					
	4		–	–	–	–	–	–	–	–	–		–	–	–	–		–	–	–	–	–	–
	5						–	–	–					–	–			–			–		
	6						–											–					
	7					–	–	–					–										
	8				–	–												–					
	9																						
	Total	0	3	3	4	5	5	4	3	1	2	2	3	4	3	3	2	6	1	2	2	1	1
Stage III	1	–		–	–	–		–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	2			–		–	–	–					–										
	3						–						–			–							
	4																						
	5						–							–	–			–				–	
	6					–									–			–		–		–	
	7				–	–	–											–	–	–		–	
	8														–						–		
	9															–					–		
	Total	1	0	2	2	4	4	2	1	1	1	1	3	2	4	3	1	5	2	3	3	3	1
I.H. > 400 M		0	0	0	0	0	0	X	X	X	X	0	0	0	0	0	0	0	X	0	X	0	0
Fog observed		Ovc	Clear	Ovc	LF	Clear	Clear	Clear	Clear	Ovc	Ovc	Ovc	Clear	F	LF	Ovc	F	F	F	LF	Ovc	LF	F

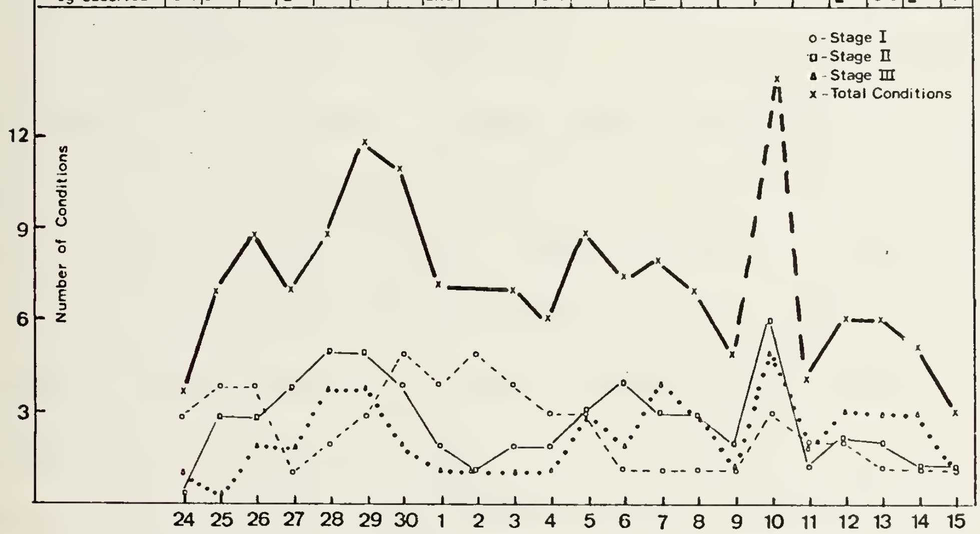


Fig. 7. Conditions for Stages I, II, and III for Monterey City Airport, Period B.
In the Tabular section a dash (-) indicates the condition was observed. Inversion Height (I.H.) > 400 meters is indicated by (X). Observed fog is indicated by F (dense fog); LF (light fog); OVC (Overcast).

the 20th at Pillar Point and Monterey, on the 21st at Point Pinos, Santa Cruz, South East Farrallon Island, and Bodega Bay. In the development model fog would have been observed at the coastal site when Stage III came into effect. The graphs and actual fog observations at the sites were in general agreement.

For the plots of total number of conditions observed, a high number of conditions seemed to indicate fog with clear skies before and after; a low number of conditions, light fog and stratus. This relationship held for all of Period A.

The table and graph for Period B indicate two time frames (24 through 29 June 1975 and 2 through 9 July 1975) in which comparison to the conditions in the development model indicated a fog sequence was in effect. Surface observations show that fog did occur at some point during each time frame. Stages I, II, and III were observed in the proper sequence for each case. The plot for total number of conditions showed the same time relationships as were shown for Period A.

The patterns observed in the tables and graphs for Periods A and B tend to support the idea that the conditions for the stages in the development model relate to observed fog situations. The graphs exhibited a sequence within the stages themselves and yet no definite break could be determined between one stage and another based on the conditions which corresponded to the observed fog. In the production of the preceding tables and graphs, the conditions of Stages I, II, and III were all weighted equally as to

whether the stage was in effect or not. No time limit of influence or index of strength was placed on the conditions, nor were interrelationships between specific conditions looked at.

B. TRENDS OBSERVED IN THE DATA

The conditions in each stage in the development model can be divided into two basic types, namely conditions which are observed only in one specific stage or conditions which can be followed through the entire sequence. The latter type of conditions will be considered in this section.

Graphs for each site were constructed for Periods A, B, and C (where data were available) for the following:

1) Maximum daily surface temperature at the inland valley versus date. (Periods A, B, and C).

2) Maximum daily surface temperature at the coastal site versus date. (Periods A, B, and C).

3) Maximum temperature at the top of the inversion versus date. (Period A, Oakland and Monterey soundings; Period B, Oakland sounding).

4) Maximum daily surface temperature at Hidden Hills versus date. (Periods A and B).

5) Maximum relative humidity at Hidden Hills versus date. (Periods A and B).

6) Height of the inversion base versus date. (Oakland or Monterey soundings).

7) Height of cloud tops and cloud bases versus date. (Period C only).

Trends were first looked for in these graphs to determine the relationship of a condition to observed fog. Next, interrelationships between conditions were sought. Composite graphs were produced of the conditions which indicated trends of importance to the fog situation. These graphs were examined for the time frames in Period A and B where the development model has been shown to be applicable.

In the following discussions of trends and relationships, Figures 8 and 9 may be referred to.

1. Maximum Daily Surface Temperature In The Inland Valley

During periods of subsidence the graphs indicated there was no appreciable difference in the temperature trends for different locations in the California inland valley. For Period A, temperatures were plotted for four inland valley stations; Fresno, Merced, Modesto, and Sacramento. The temperature trends held for each site during the entire period, with the only difference observed being a slight decrease in the maximum temperature the farther north the station was. Period C showed the same characteristics of no difference in temperature trends for Fresno and Sacramento, with only a slightly lower temperature being observed at Sacramento. Maximum daily surface temperatures for NAS Lemoore (27 miles from Fresno) were available for Period B. Due to the proximity of Fresno and Lemoore and their relative position in relation to Monterey, the remaining discussions of maximum inland valley temperatures will utilize values from these sites.

From day to day, the temperatures in the inland valley varied gradually in each period. Generally the maximum surface temperatures attained values above 30 C in strong subsidence periods. Fog was not observed on the coast for any of the cases studied when the maximum surface temperature in the inland valley was below 30 C. Fog was observed on the coast after non-fog periods when temperature rises of from as little as 1-1/2 C to as much as 9 C occurred in the valley. The normal case was for fog to form at the coast after the minimum value in the valley cycle had been reached and the temperature maxima had risen from 3 to 6 C over a two- to four-day period.

2. Maximum Daily Surface Temperature At The Coastal Site

The trends in maximum daily surface temperature at coastal sites were investigated for trends in the temperature before fog was observed, during the period fog was observed, and after the fog was observed.

Twenty-nine blocks of days when fog was observed were looked at during the three periods. Increasing temperatures were generally observed on the coast prior to the day fog was first observed with a drop in maximum surface temperature on the first day of fog. When fog was observed on more than one day during a case, the temperature pattern showed no reliable increasing or decreasing trends. This was also the case on the day after fog was no longer observed.

3. <u>Maximum Temperature At The Top Of The Inversion</u>

Graphs of maximum temperatures at the inversion top were made from raobs taken at Monterey and Oakland for Period A and Oakland for Period B. The trend in these temperatures proved to be similar for both sites in Period A.

The temperature sequence appeared cyclic in nature for both Periods A and B. The inversion-top temperature at which fog was first observed did not show a dependence of fog on a specific temperature, but fog was observed to occur only during periods of steady temperature rise above a low maximum temperature of 20 to 25 C and prior to the highest maximum temperature in the cycle being reached. When the temperatures were in the low 20s, a 4 to 6 C increase in inversion top temperature seemed to be necessary before the initial fog was formed on the coast. Continued maximum temperature increase corresponded to a lengthening in time the fog persisted each day. After the highest maximum temperature was reached a steady decrease occurred. Overcast or light fog were observed as the temperature fell off.

4. <u>Daily Maximum Surface Temperature at Hidden Hills</u>

Daily maximum surface temperatures and minimum relative humidity data for Periods A and B were plotted for Hidden Hills, California. This site is maintained by Dr. Leipper at his home, which is 12 miles from Monterey and situated 850 feet above msl between the Salinas and Carmel valleys.

The trends in the daily maximum surface temperature at Hidden Hills followed much the same patterns as those described for daily maximum temperatures in the inland valley and at the top of the inversion. The amount of temperature increase rather than a specific temperature was again seen to be an important factor. Initial fog formation was observed to occur after a steady increase in temperature of from 4 to 7 C in each period. The rate of day to day increase in the temperature appeared to be an indicator of the number of days required and the amount of temperature increase needed before fog was observed.

5. Minimum Daily Relative Humidity at Hidden Hills

Daily minimum relative humidity at Hidden Hills was seen to be inversely related to the daily maximum temperature observed. A significant drop in the daily minimum humidity was observed to occur on the day fog was initially observed at the coast in each period.

6. Height Of The Inversion Base

The height of the inversion base was extracted from raob data from Monterey and Oakland for Period A and Oakland for Period B. The trends observed for both Oakland and Monterey were similar in Period A.

The 400-meter level was seen to be a critical height for the inversion as it related to observed fog at the coast. If the inversion was at or near the surface, fog was not observed at the coastal station providing data. A steady increase in the inversion height toward the 400-meter level

over a period of days corresponded to a sequence beginning with a dense fog of short duration occurring on the initial fog day with clear skies before and after. Further increase in inversion height on succeeding days up to the 400-meter level related to dense fog being observed for longer durations. When the inversion height hovered around the 400-meter level there was light fog and overcast. A decrease in inversion height to a level below the 400-meter level corresponded to dense fog again being observed at the coast with clear skies before and after.

7. Height of Cloud Tops And Cloud Bases

The primary consideration for selecting Period C was the availability of a set of pilot reports for Monterey of cloud "tops" and "bottoms" in the Appendix of a report by Cole (1964). There is a paucity of direct observations of this type in the literature and most estimates of stratus thickness are made on the basis of lifting condensation level and inversion height information. [Rosenthal (1972) states that while stratus may penetrate through the inversion, the base of the inversion is generally a good approximation to the top of the clouds. Ceilings may be measured directly and assumed to be at the cloud base.]

Two hundred and fourteen pilot reports were made from 18 May 1964 to 18 September 1964, the same period of the year that the development model should be effective. The data were plotted on the basis of cloud top and bottom

versus date. Average cloud thicknesses were determined from the data and are presented in Table 3.

Table 3

Monterey Average Cloud Thickness, 18 May-18 September 1964

Height of Cloud Top (ft)	Number of Observations	Average Δz (ft) (Top - Base)
0 - 1200	29	547.4
$1200<T\leq 2000$	132	944.9
>2000	58	1244.8
Total Observations	219	921.02

These calculations were found to be in excellent agreement with those of Point Mugu where typical heights for stratus tops were in the range of 1000 to 2000 feet with 500 to 1000 feet being the typical estimated thickness or depth of the stratus layers (Rosenthal 1972).

Daily surface observations for Period C were plotted from NAF Monterey data archived at NPS. When compared to the graphs for cloud "tops" and "bottoms" it was observed that when no pilot reports for a day were given, either clear conditions were observed at NAF Monterey or fog and low overcast below flight minimums were reported. When the daily height of the cloud tops were compared to daily fog observations for Monterey, trends comparable to those found for the height of the inversion base in Periods A and B, and observed fog, were found. The approximation of the height of the stratus tops for the height of the inversion could be used when no raob data for an area was available.

8. <u>Observed Interrelationships</u>

The graphs of the individual conditions were compared to determine if any interrelationships between conditions were evident.

A general relationship was observed to exist between the maximum daily surface temperature in the inland valley and the maximum daily surface temperature at coastal sites. Except in the cases of strong frontal activity, an increasing trend in the inland valley maximum surface temperature corresponded to an initial rise in the maximum surface temperature at the coastal site. However, as in the inland valley continued to heat, a general lowering was exhibited in the daily maximum surface temperatures at the coast.

The graphs for maximum daily surface temperature in the inland valley and maximum temperature at the top of the inversion at the coast displayed patterns in their increases and decreases so closely related that, except for the difference in the absolute temperatures, one could be used in lieu of the other. No direct mechanism, other than subsidence as reported for example by Blake, was apparent for this correspondence, but it held throughout Periods A and B. In the remaining discussion, except where absolute values of temperatures are important, relationships observed for one can be considered to apply equally to the other.

The maximum daily surface temperature at Hidden Hills followed approximately the same pattern as that observed for the temperature at the top of the coastal inversion with one

important difference. The Hidden Hills temperature appeared slightly out of phase with the temperature at the inversion top, and reached its maximum and minimum temperatures one to two days earlier. The maximum surface temperature at Hidden Hills followed a trend reverse to the daily minimum relative humidity at Hidden Hills. A rise in temperature was accompanied by a fall in daily minimum relative humidity.

If over a period of days the height of the inversion base was seen to start with unusually warm air at or near the surface, general relationships to the other conditions could be observed.

Maximum daily surface temperature in the inland valley, maximum temperature at the top of the coastal inversion, and maximum daily surface temperature at Hidden Hills all exhibited a similar relationship to the height of the inversion base. If the three temperatures were observed to increase steadily on a daily basis and the inversion height was initially at or near the surface, a steady rise in the inversion height toward the 400-meter level as long as the daily maximum temperature in the inland valley and at the top of the inversion were increasing toward their highest daily maximum. When the trend of these temperatures was seen to become a decreasing one, the height of the inversion base was seen to rise above the 400-meter level. If an increasing trend in the two temperatures was again observed, the height of the inversion base again dropped below the 400-meter level. The same trends were generally true for Period C where heights

of the cloud tops were used. Increasing temperatures in the 20 - 25 C degree range for daily maximum temperature at the top of the inversion appeared to be associated with low inversion heights. This temperature range was also significant for the Hidden Hills maximum surface temperatures. The Hidden Hills daily maximum surface temperature was observed to be slightly out of phase with the trends for maximum daily surface temperature in the inland valley and at the top of the inversion. Since the Hidden Hills daily maximum surface temperature began its increasing trend prior to those observed for the other two conditions and also reached its maximum and minimum temperatures earlier, it possibly could be used as an excellent indicator for estimating when the inversion height would reach and exceed the 400-meter level.

A comparison of the graphs for daily minimum relative humidity at Hidden Hills and height of the inversion base have basically the same pattern. Low minimum relative humidity at Hidden Hills corresponded to a low base of the inversion on the coast and relatively high minimum relative humidity corresponded to heights of the inversion base above 400 meters. Trends of increasing relative humidity at Hidden Hills were seen to correspond to a subsequent increase in the inversion height.

A height of the inversion base of 400 meters was observed to be an important indicator of when drizzle would be observed. During Periods A and B drizzle was reported at the coastal site initially as the height of the inversion

base rose to 400 meters and during the periods the height of the inversion base hovered at or near the 400 meter level. Rosenthal (1972) reports that for Point Mugu drizzle occurs when ceilings are in the 100 to 300 foot range and only rarely will measurable precipitation occur with drizzle. Drizzle at Point Mugu was also more likely with thicker stratus.

C. COMPOSITE GRAPHS

Composite graphs (Figures 8 and 9) for Monterey were constructed for Periods A and B in order to prominently display the day by day trends and relationships discussed. Days on which drizzle occurred and the hourly visibility and cloudiness plots are also shown. Monterey was specifically considered due to the availability and applicability of the Hidden Hills data. The complete time frames for Periods A and B were used so that a comparison could be made to Figures 6 and 7 which displayed the stages of the development model based on the number of conditions observed.

The time frames from 19 August through 25 August 1974 for Period A and from 24 June through 29 June and 2 July through 9 July 1975 for Period B have been pointed out from Figures 6 and 7 as periods in which comparison to the conditions in the development model indicated a fog sequence was in effect. Figures 8 and 9 were looked at for the same time frames. The height of the inversion base was noted to be at or near the surface at an early point in each period the development model indicated a fog sequence was in effect. If the trends

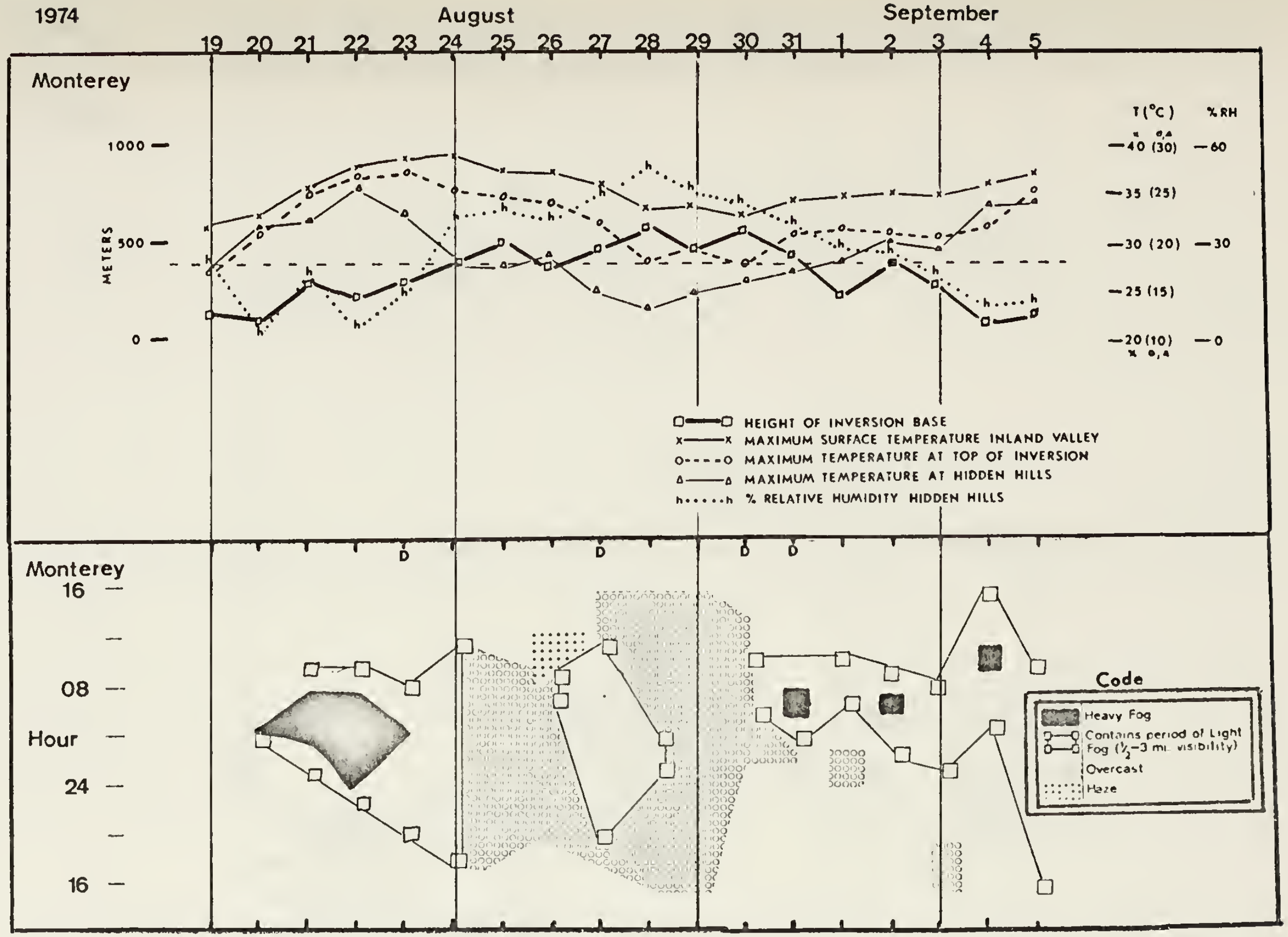


Fig. 8. Composite graph displaying the day-to-day trends and relationships to observed visibility and cloudiness at Monterey City Airport. D indicates days on which drizzle occurred. Monterey soundings used for height of inversion base and maximum temperature at top of the inversion.

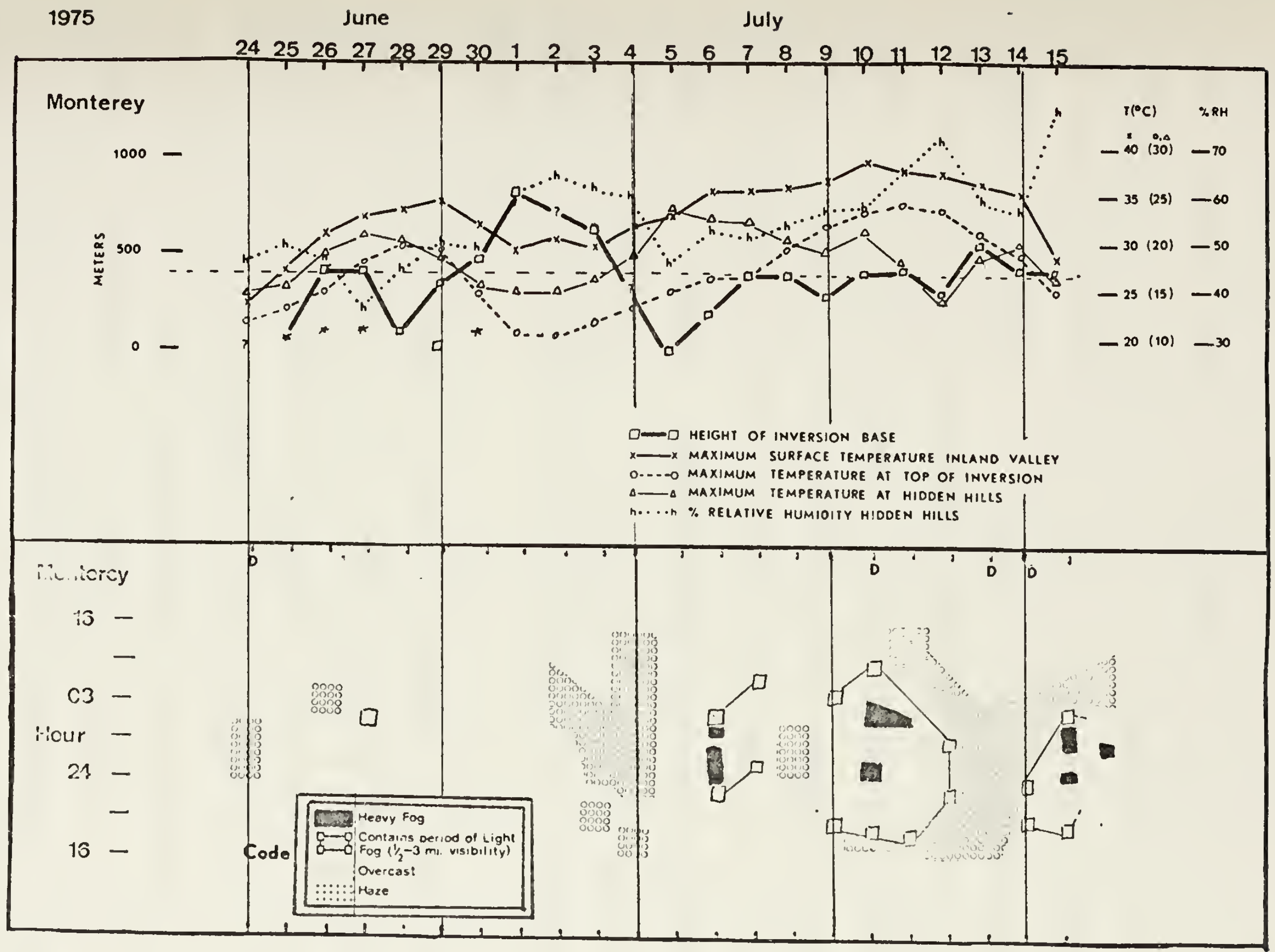


Fig. 9. Composite graph displaying the day-to-day trends and relationships to observed visibility and cloudiness at Monterey City Airport. D indicates days on which drizzle occurred. Oakland sounding used for height of inversion base and maximum temperature at top of inversion.

displayed by the other factors in Figures 8 and 9 were favorable for fog occurrence and the height of the inversion base began at or near the surface and increased toward the 400 meter level, it was a significant indicator of what the surface observation on a given fog day would reflect. The height of the inversion base also appeared to be an indicator of the diurnal duration dense fog would be observed as the sequence proceeded. Although Figures 7 and 8 indicated the development sequence ended when the height of the inversion base reached the 400-meter level, Figures 9 and 10 showed that as long as the inversion base remained in the vicinity of 400 meters, observed conditions related to the end of Stage III remained. Surface observations corresponding to Stage II and Stage III were noted to re-occur when the height of the inversion base dropped well below the 400-meter level.

A prime example of why the height of the inversion base could not be used as the only condition is seen during the time frame 28 June 1975 through 4 July 1975 on Figure 9. If the rise in the height of the inversion base alone was considered fog would be expected to be observed on the 29th. No fog was observed. The trends observed for the conditions of temperature at the top of the inversion, maximum surface daily surface temperature in the inland valley and at Hidden Hills do not indicate fog.

V. AN OBSERVED FOG-STRATUS DEVELOPMENT

Figure 6 has indicated that during the period 19 - 25 August 1974 a fog system developed at Monterey indicative of the development model. Similar figures, though not presented, for the other sites in Figure 2 suggested that the system developed over an extensive area along the California coast. This indication was strengthened by Figures 3 and 4 in which the surface observations for each coastal site from Point Pinos to Bodega Bay showed a pattern for reported conditions which corresponded to Stage III of the development model. It can also be noted from Figures 3 and 4 that the development appears to have a south to north progression with fog occurring and being reported at a slightly later date the further north the site. From Figure 8 it was determined that the height of the inversion base was a significant indicator of what the surface observation at a coastal site on a given fog day would reflect.

The above determinations generally reflect and confirm Stage III of the development model which comes into effect when fog is observed at the coast.

In order to present the entire development sequence as it formed during this period, satellite photographs, surface weather maps, raob data for Point Mugu, Monterey, and Oakland, and related sea surface structure will be considered.

A. SATELLITE PHOTOGRAPHS

Wallace (1975) found for daytime visual (SRVIS) NOAA II satellite imagery that for areas unobscured by middle- and high-level clouds, it was possible to pick out areas of low-level clouds and further distinguish stratus and/or fog from cumulus type clouds. Grey shade variations in the satellite imagery were noted in areas where fog was reported, particularly along the discernable boundaries of varying grey shades which coincided with fog/no fog boundaries. Wallace also pointed out that there was no apparent grey shade variation detectable between areas reporting fog and those reporting stratus in a more or less continuous layer in the NOAA II imagery.

Based on these findings it was determined that although the SRVIS NOAA II satellite photographs available for the period 20 through 25 August 1975 could not in themselves be used to determine whether fog was or was not present at a specific location, they would indicate whether a general fog/stratus development occurred and the trends in that development.

In Figure 10 is shown the surface weather map for 19 August 1975. In Figures 11 through 16 are shown six successive SRVIS NOAA II satellite photographs and the corresponding daily surface weather maps for 20 through 25 August 1975. These surface weather maps and satellite photographs indicate that a fog/stratus situation did develop in a manner consistent with the development.

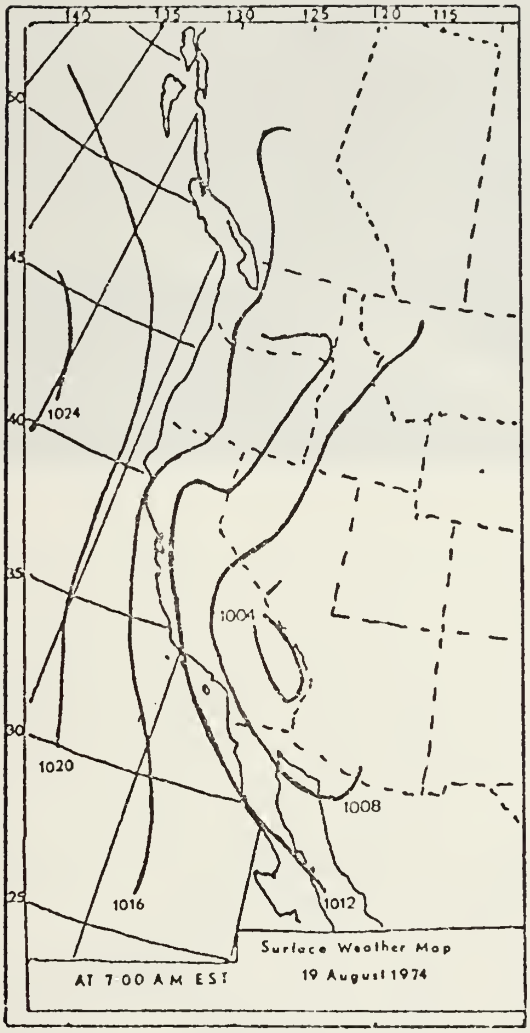
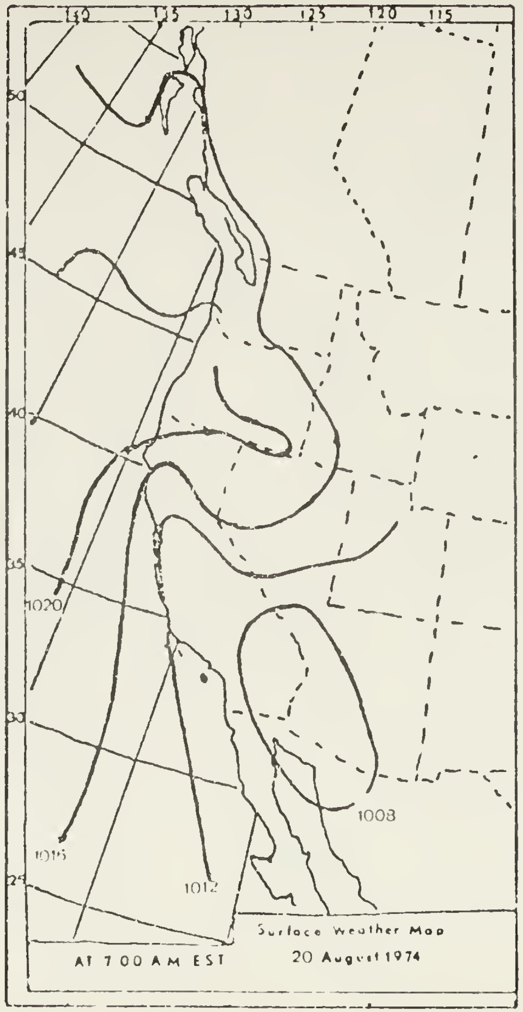


Fig. 10. Fog/Stratus Development 19-25 August 1974.

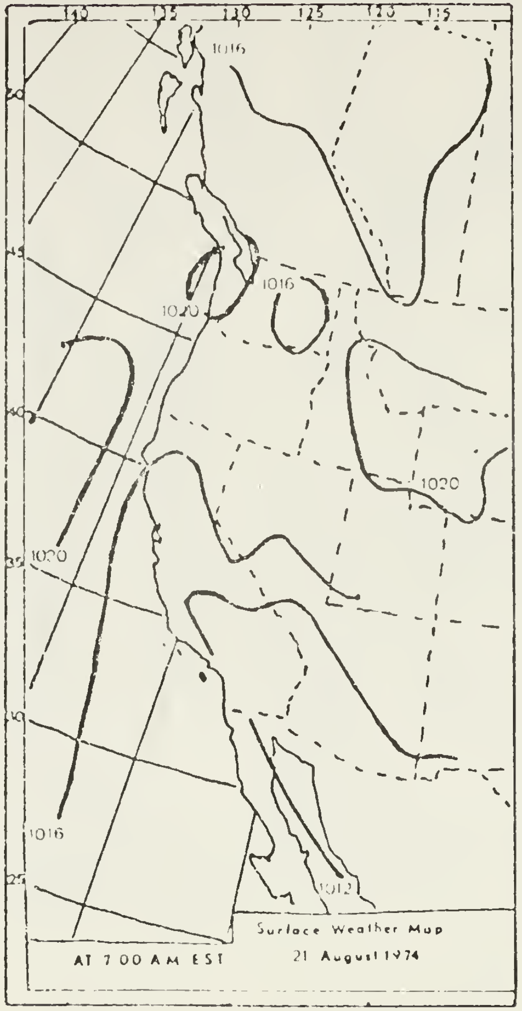
(a) Surface Weather Pattern indicative of Stage II of Development Model.



(b) NOAA II Satellite Photograph of a Fog/Stratus System Development off the West Coast at 17:03 GMT, 20 August 1974.

Fig. 11. Fog/Stratus Development 19-25 August 1974
Early Stage II.

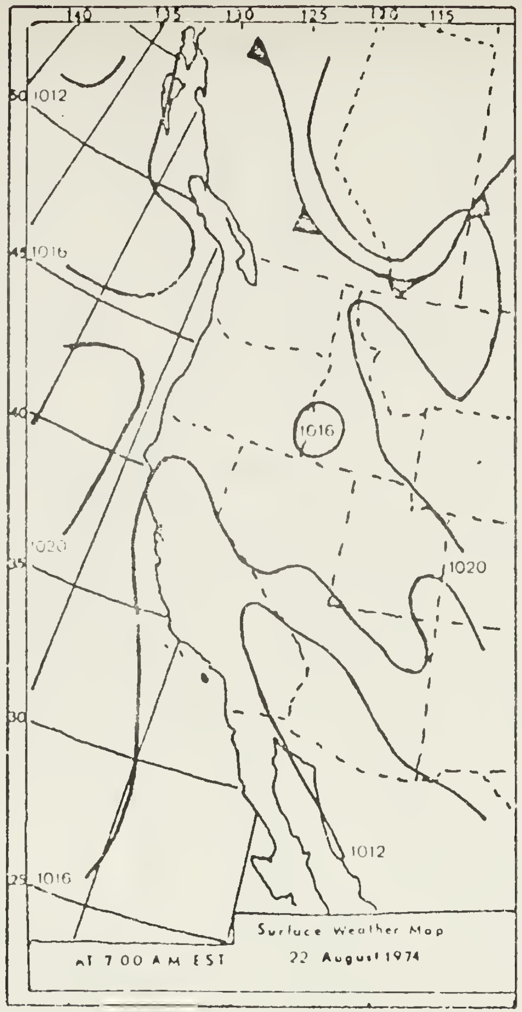
(a) Surface Weather Pattern
21 August 1974



(b) NOAA II Satellite Photograph of a Fog/Stratus System Development off the West Coast at 18:13 GMT, 21 August 1974.

Fig. 12. Fog/Stratus Development 19-25 August 1974.
Late Stage II, Early Stage III.

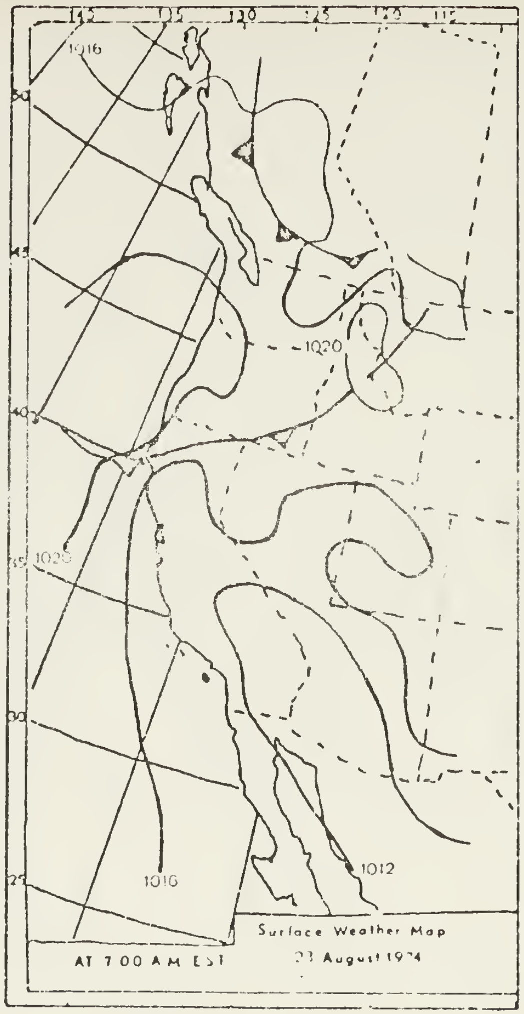
(a) Surface Weather Pattern 22 August 1974.



(b) NOAA II Satellite Photograph of a Fog/Stratus System Development off the West Coast at 17:27 GMT, 22 August 1974.

Fig. 13. Fog/Stratus Development 19-25 August 1974. Stage III.

(a) Surface Weather Pattern
23 August 1974



(b) NOAA II Satellite Photograph of Fog/Stratus System Development off the West Coast at 18:33 GMT, 23 August 1974.

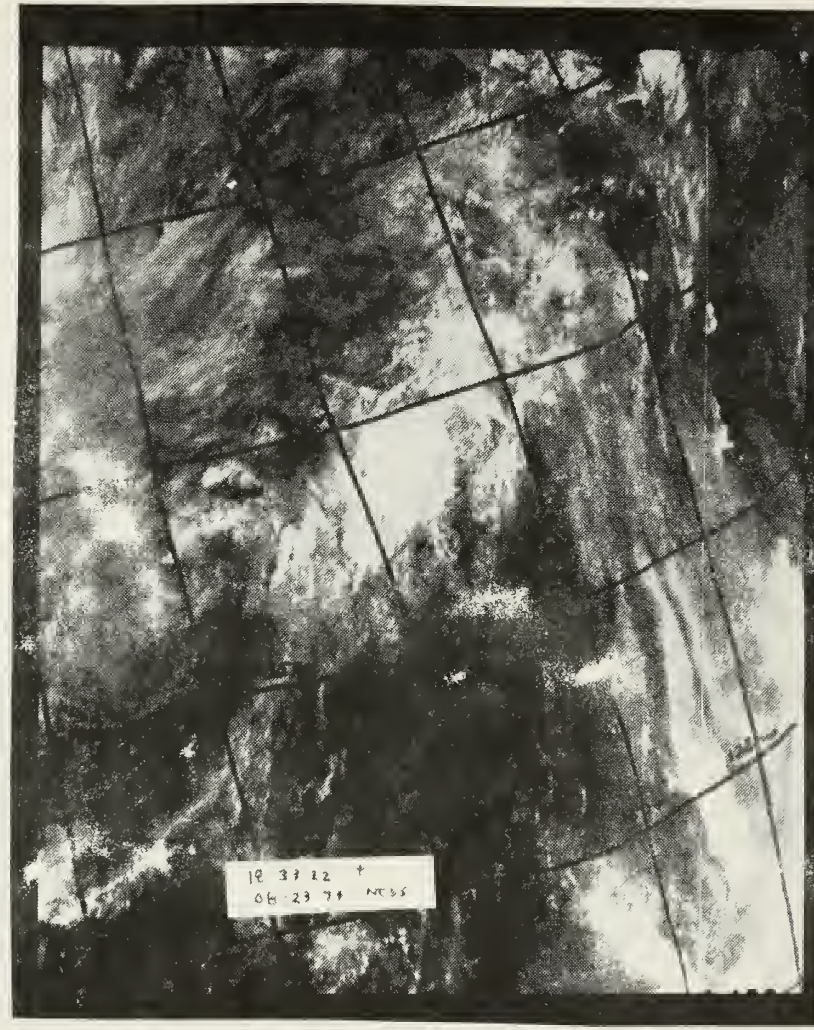
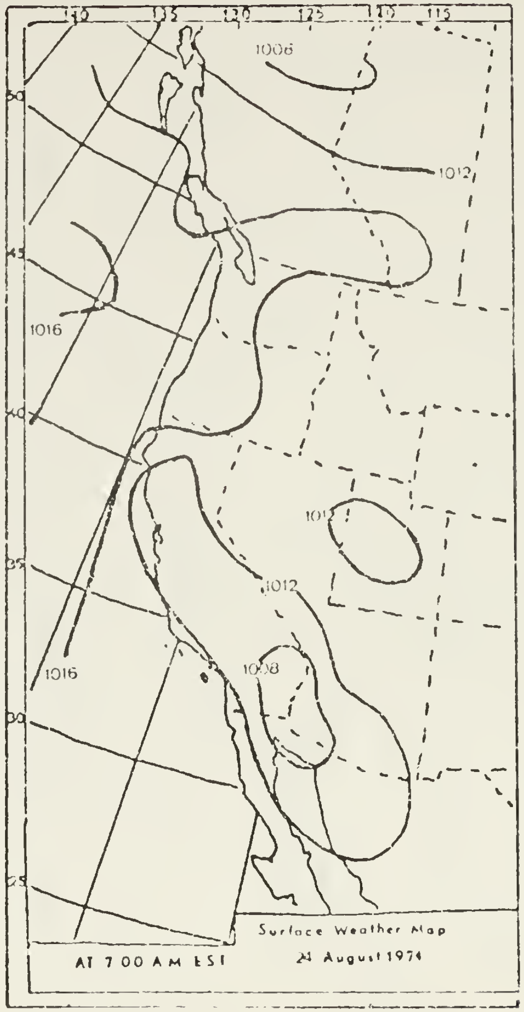


Fig. 14. Fog/Stratus Development 19-25 August 1974
Stage III.

(a) Surface Weather Pattern
24 August 1974



(b) NOAA II Satellite Photograph of a Fog/
Stratus System Development off the West
Coast at 17:46 GMT, 24 August 1974

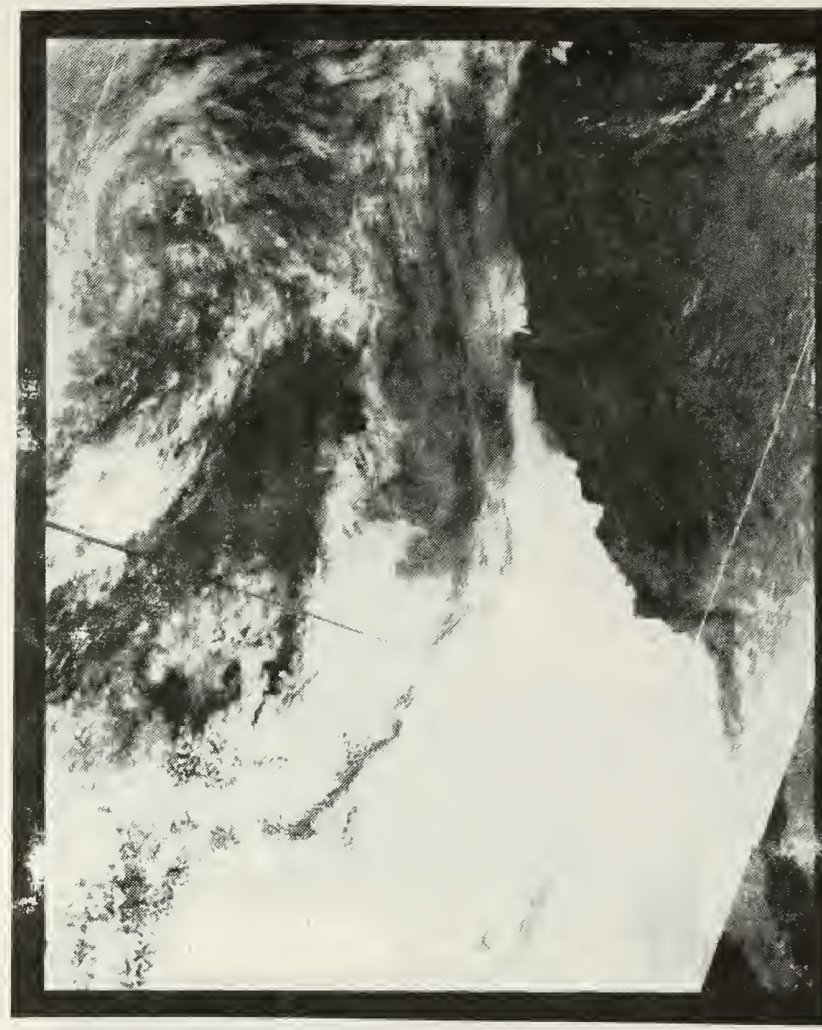
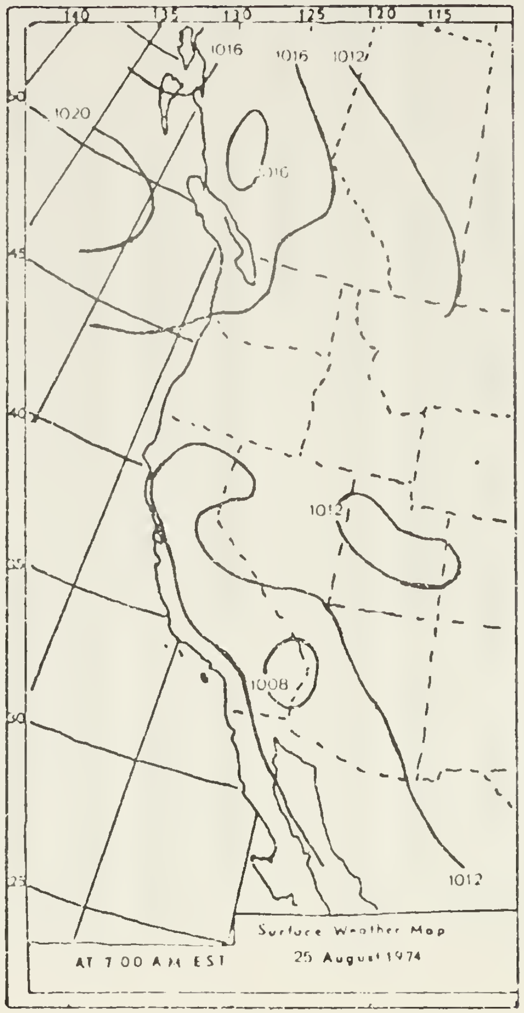


Fig. 15. Fog/Stratus Development 19-25 August 1974
Late Stage III.

(a) Surface Weather Pattern
25 August 1974



(b) NOAA II Satellite Photograph of a Fog/Stratus System Development off the West Coast at 17:06 GMT, 25 August 1974

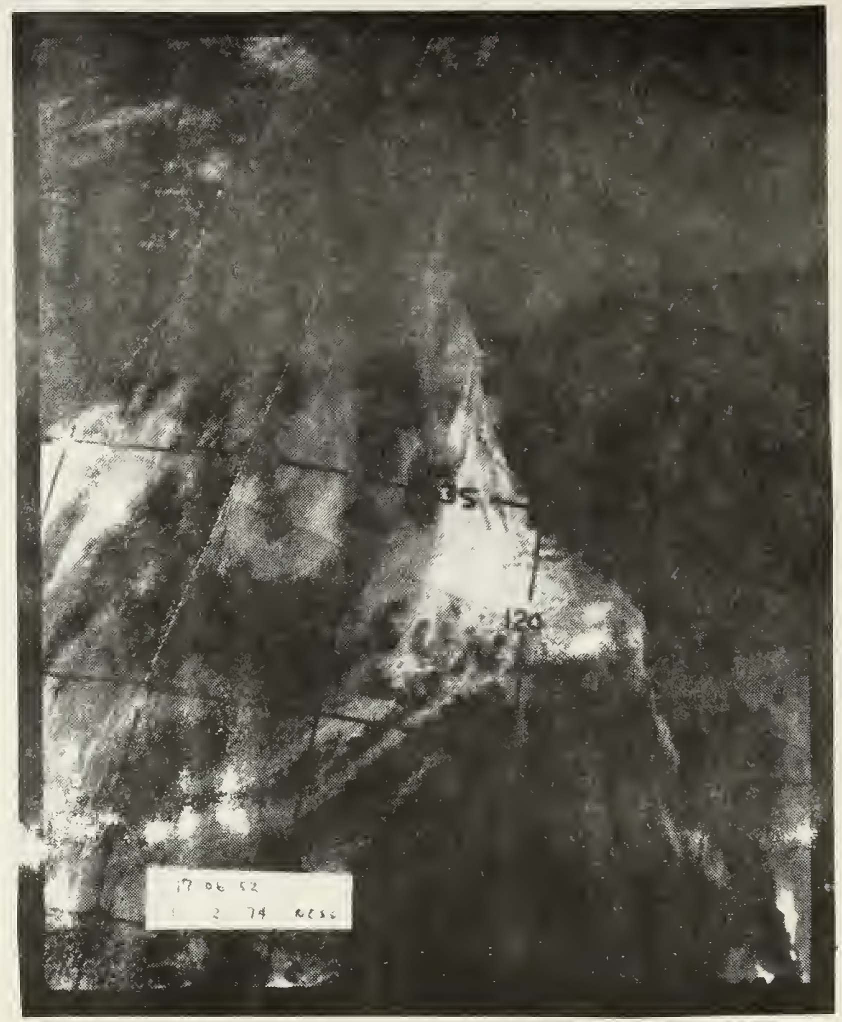


Fig. 16. Fog/Stratus Development 19-25 August 1974
Late Stage III. Overcast Observed at Coastal Sites.

In Figure 10 the surface weather map shows the position of the eastern North Pacific subtropical high and an isobaric pattern indicative of Stage I of the development model. Although no satellite photo was available for this day, Figures 3 and 4 show the sites north of Point Mugu were experiencing clear conditions on the coast. Surface air temperatures warmer than the sea surface temperature were also reported in sporadically spaced ship reports along this segment of the coast. These observations are also indicative of Stage I.

An initial attempt was made to take visibility, surface air temperature, and wind speed and direction from weather maps containing surface ship reports. Due to the quality of the maps and the number, the positions and spacing of the ships, only limited use could be made of these maps. The area in which these maps were found the most useful was in determining the general surface wind pattern off the coast for this period. Appendix B in the master copy of this study contains the daily plots of the winds along the coast obtained from these maps.

In Figure 11 the satellite photograph shows patterns consistent with the conditions of Stage II of the development model. The eastern North Pacific subtropical high is seen to have pushed well inland over extreme northern California and Oregon, with the thermal trough having increased in strength in the California inland valley, resulting in the isobar pattern remaining almost parallel to the central

California coast. The satellite photograph in the same figure shows a clear tongue of air extending over the coastal oceanic region from the north to the Point Mugu area where a fog/stratus situation is already evident on the coast. The clear air defines the area over which the initial conditions for continued fog development at sea may be considered.

In Figure 12 the satellite photograph indicates that the fog/stratus situation in the south has moved north along the coast up to Monterey Bay. Over the water adjacent to the coast north of Monterey where only clear conditions were observed in Figure 11, a shade of grey becoming lighter from the coast seaward is now observable. Based on the work of Wallace (1975), this would seem to indicate that shallow fog is present in these areas. The sea-surface temperature pattern for the period is given in Figure 1. The areas of grey shading correspond well with the colder waters found along the coast. This is indicative of what should be observed in late Stage II north of Monterey, and early Stage III immediately south of Monterey.

In Figure 13 the development of a distinct wedge of fog/stratus is observed to extend over several hundred miles of the coast and broaden significantly to the south. In Figures 3 and 4 heavy fog is observed to occur at the coastal sites. Stage III appears to be well developed.

In Figures 14, 15, and 16 the general conditions of the end of Stage III are observed with the fog/stratus layer extending farther inland.

B. VERTICAL SOUNDINGS OF THE ATMOSPHERE

It has been recognized for some time, e.g. Leipper 1948, that vertical soundings of the atmosphere would supply important data to be used in the formation and persistence of marine fog over the water as well as land. Soundings above the water surface were not available except in the extreme northern portion of the area from the ACANIA during the Calspan cruise. These soundings did not generally reach sufficient altitude to determine the needed parameters (height of the inversion base and maximum temperature at the top of the inversion). However, because of the nearness of the ocean and the observed surface weather patterns, extrapolation of the raob data from Point Mugu, Monterey, and Oakland to the offshore situation was deemed useful for presenting the overall observed development.

In Figure 18 are shown the soundings for the three sites, Point Mugu, Monterey, and Oakland. The soundings in Figure 18 are early morning observations taken at approximately 0400 PDT and are presented on an every other day basis from 20 August through 28 August 1974.

The soundings for Point Mugu in Figure 17 show that on the 20th of August the surface inversion has already formed and the surface air temperature is lower than the sea-surface temperature. This is indicative of late Stage II in the development model. Haze is observed to have preceeded light fog on the coast at approximately 0100 PST on the 19th of August. The satellite photo Figure 11 for the 20th indicated

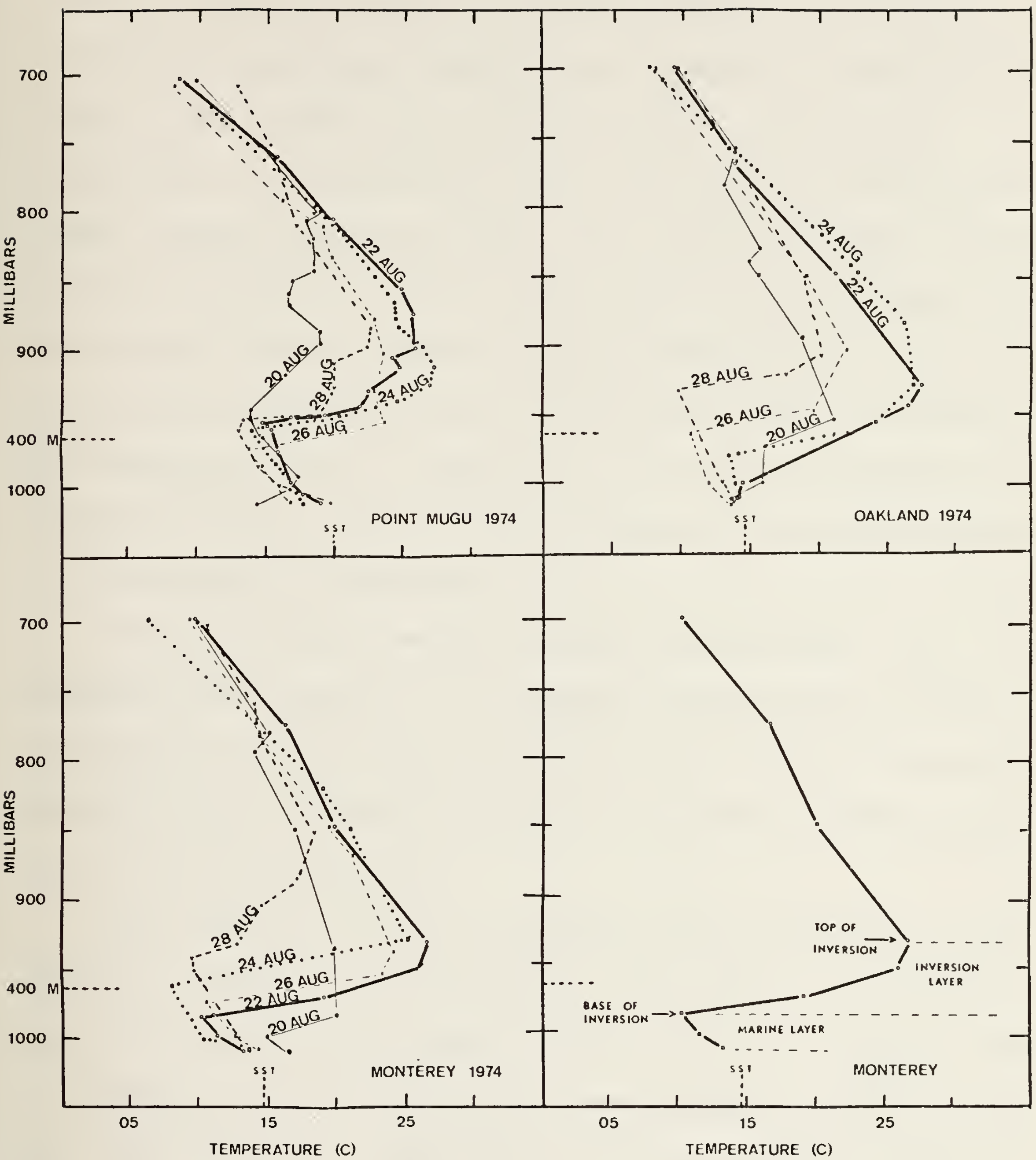


Fig. 17. Vertical Soundings at Point Mugu, Oakland, and Monterey during a Fog/Stratus Development 19-28 Aug. 1974.

that a heavy build up of fog (stratus covered the entire area from Point Conception north of Point Mugu south past the U.S. Mexican border). In the sounding for 22 August 1974 the marine layer has deepened to greater than 400 meters with a haze, light fog, and low overcast restricting visibility. This indicates that Stage III has occurred between the two soundings shown. The satellite photo indicates that the fog/stratus layer had penetrated well inland in the Point Mugu area and appears to have intensified. The sounding for the remaining days of the period show the height of the inversion base to remain at or near the 400-meter level with the surface observations confirming that the conditions of late Stage III remained.

Except for the sounding on the 20th of August for Monterey, the soundings for Oakland and Monterey in Figure 17 show structures which are consistent with the development model and the observation both on the satellite photographs and at the coastal sites.

The Oakland soundings are almost ideal examples of the sequence given in the development model for the inversion structure expected in Stages II and III. On 20 August 1974 the Oakland sounding shows the inversion base at the surface and the surface air temperature is lower than the sea-surface temperature. This indicates that Stage II is in effect. Fog was not reported at the coastal sites, but the satellite photograph in Figure 12 showed a light grey shade over the coastal water which may indicate a shallow fog formation.

The sounding on 22 August 1974 for Oakland indicates the presence of a shallow mixed layer in which the air is cooler than the sea surface. The temperature at the top of the inversion shows the highest temperature in the sequence. Heavy fog was observed at Pillar Point on the coast for ten hours. Stage III of the development model is indicated. In the sounding for 24 August 1974 the height of the inversion base has raised to the 300-meter level with the temperature at the top of the inversion showing a slight decrease. Heavy fog was still observed at the coast. In the sounding for 26 August 1974 the height of the inversion base has raised to the 400-meter level and the temperature at the top of the inversion has lowered toward the sea surface temperature. This would indicate that the later part of Stage III is in effect.

C. SEA SURFACE TEMPERATURES

The fifteen-day average sea-surface temperature for 16 through 31 August 1974 for the California coast is shown in Figure 1 and displays the typical upwelling season pattern with packets of lower temperatures adjacent to the coastline northward from Point Conception. The satellite photograph in Figure 12 for 20 August 1974 gave an indication that initial fog formation over the ocean occurred adjacent to the coast over the areas of colder water. The satellite photograph for 21 August 1975 indicated a possible spread of the shallow fog layer over a larger area of the ocean surface.

This would seem to indicate that after the initial formation of marine fog over cool water, results from cooling below, it may be carried over warmer water and still persist. However, no useful shipboard observations were available to substantiate this on the 20th and 21st of August in the development area.

Data were presented for the same fog/stratus development system in a Calspan Report, "Marine Fog Studies Off The California Coast" (Mack 1975), for three east-west tracks conducted from 0520, 23 August 1974 to 0200, 25 August 1974. The three tracks were crosswind traverses through the fog/stratus system. The area of the traverses was north of Cape Mendocino offshore from Eureka.

Visibility, air temperature, and water temperature data along the crosswind tracks were presented. Changes in air temperature were seen at times to be directly correlated with sea surface temperature. That major fog areas were associated with regions of abruptly colder water was also pointed out as being evident from comparison of the visibility and sea surface temperature.

The development model indicated that conditions in Stage III were in effect during the above crosswind tracks. Stratus or surface fog were reported as existing near the coast during each track.

The same type of relationships were observed for visibility, air temperature, and water temperature data during

a short fog data gathering cruise by the ACANIA on 11 June 1975 off Monterey.

During this cruise low overcast with ceilings from 100 - 300 feet were observed from the coast seaward with visibilities generaly greater than three miles. A narrow fog bank was located oriented north - south off Point Pinos and passed through between 0615 to 0645 hours. Visibilities were between 1/4 - 1/2 mile. The course of the ship was reversed and the area re-entered at 0700 and the ship allowed to drift. Visibility had increased to one mile by this time. A sounding was taken at 0720 with the visibility still at one mile. The ACANIA departed the area at 0730 and proceeded seaward, with steadily increasing visibility being observed. The course was again reversed and low visibilities were encountered again in the original fog area at 0845. Visibilities were observed to have decreased along the coast to one mile on the transit to Monterey. Figure 19 gives the visibility, sea-surface temperature, surface air temperature, and wet-bulb temperature for this period. Two soundings are also presented. The ACANIA sounding taken at 0720 utilized a standard XBT temperature probe with the weights and Tailfin section removed. A weather balloon was used for ascent and ascent rate calculated. The temperature trace was taken from the XBT recorder. This method of obtaining upper air soundings at sea is being tested by T. Calhoun and J. Norton at the Naval Postgraduate School. The Oakland sounding taken at 0400 PST is given for comparison.

Changes in surface air temperatures and sea-surface temperatures can be seen to correspond. The fog area encountered was associated with a region of abruptly colder water, with the surface air temperature being observed to be close to or below the sea-surface temperature. The ship's track was crosswind to the fog area.

The ACANIA and Oakland soundings were seen to be in general agreement except for the slight temperature increase with height in the first 50 meters of the ACANIA sounding.

The two significant features in the above data were (1) the position of fog was correlated with abrupt gradients in sea-surface temperature; and (2) the air temperature within fog was close to or below the sea-surface temperature. Similar features were observed in the Calspan cruises (Mack 1975).

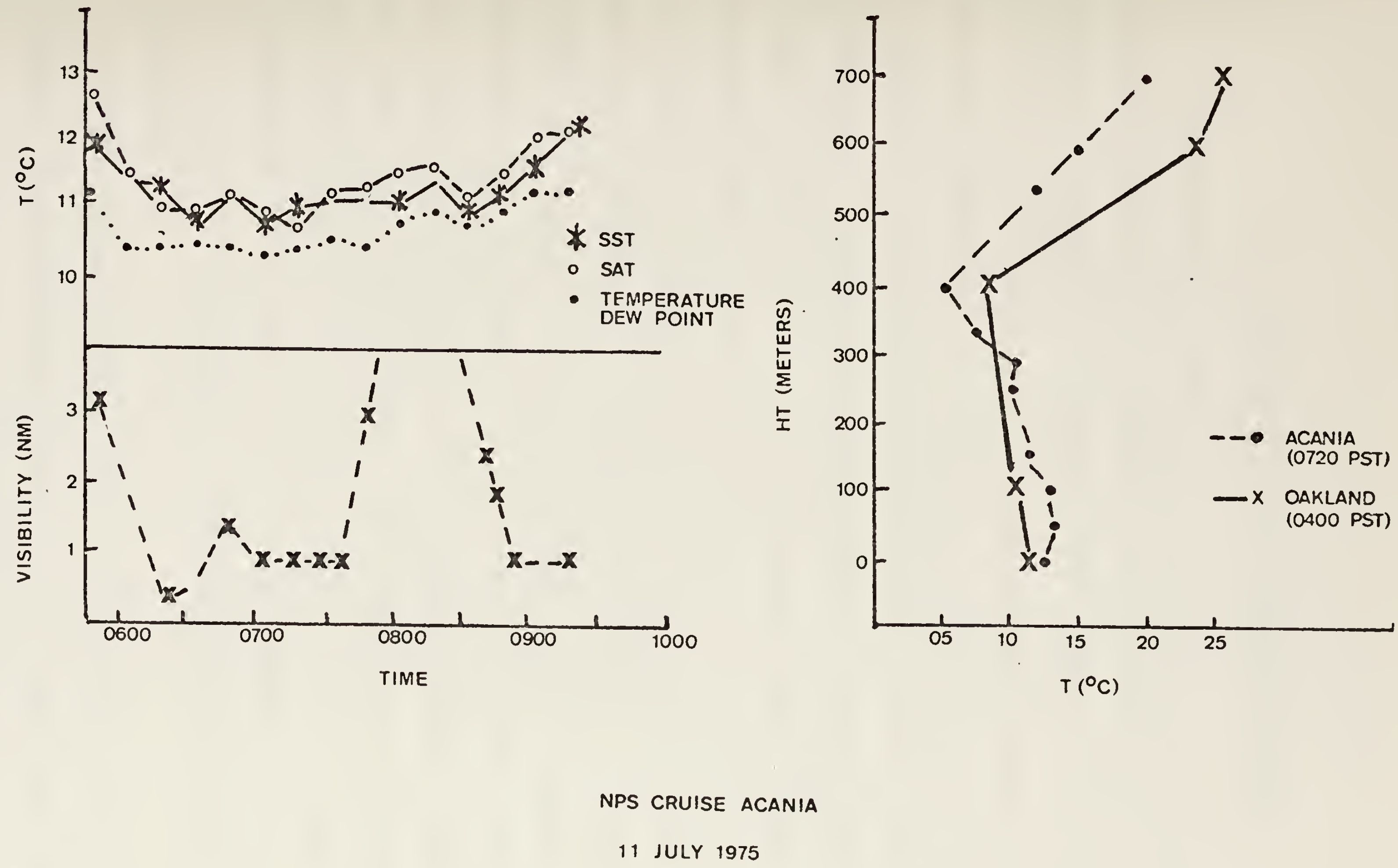


Fig. 18. Visibility, Air and Water Temperatures and Vertical Soundings for NPS Fog Cruise 0600 - 0930 PST, 11 July 1975.

VI. CONCLUSIONS AND RECOMMENDATIONS

From observing actual fog developments at Monterey, an intuitive feeling was gained that the occurrence of fog was based on a sequence similar to that which occurs on the southern California coast. This sequence seemed to begin some days previous to the initial fog day and continue through a period of days during which fog was observed until overcast prevailed. For the California summer period segments of sequences were found in the literature which seemed to fit synoptic-scale fog/stratus developments. With the exception of Leipper's 1948 model for San Diego and its extension to the summer period in that area, no complete sequence of conditions was given for west coast fog development. Nor, was any other systematic way of presenting and evaluating the conditions pertaining to a fog-development sequence for the coast as a whole noted. This study has considered both the organization of conditions which relate to west coast fog/stratus developments and the relationship of a number of non-diurnal conditions to selected observed fog/stratus situations.

The development model used in this study was an attempt to place the conditions related to the fog/stratus situation into a sequence of conditions broken into three stages. Evaluation was made on the basis of data available for periods when fog was actually observed at coastal sites. The hourly visibility and cloudiness graphs were used to present the

actually reported visibility and cloudiness at the coastal sites. These graphs were found to be a most satisfactory method of concisely displaying a large amount of data covering a period of days. Although the development model was general in nature, it is believed that sufficient evidence is presented to justify further investigation and refinement of this method for studying fog development along the central California coast.

The visibility and cloudiness graphs generated for the sample periods used in this study support the hypothesis that fog occurs over large areas of the coast in blocks of fog days. Moreover, the time at which the fog affected each coastal site appeared to be related to the relative north-south position of the site. This was especially true if clear conditions were reported prior to the initial fog day in the block. If this was the case at the coastal sites, a definite sequence was observed. This sequence was:

1) Clear conditions reported for an entire day.

2) Light fog turning to dense fog, preceded and followed by clear conditions, with the diurnal duration of fog being observed to increase on a day-to-day basis.

3) Light fog preceded and followed by overcast.

4) Overcast conditions prevailing with no fog.

Trends were observed in several non-diurnal conditions which related to this sequence. These trends were:

1) Increases in the height of the inversion base in the zero to 400 meter range.

2) Increases in the daily maximum temperature at the top of the inversion above the 20 to 25 C level.

3) Increases in the daily maximum surface temperature in the inland valley above the 20 C level.

For Monterey, specifically, trends in the daily maximum surface temperature and minimum daily relative humidity at Hidden Hills showed promise as a method of determining when fog would develop at Monterey.

During the course of this study a number of problem areas were encountered which directly affected the ability to obtain more specific results. Several recommendations can be made on the basis of experience gained in this study.

One of the principle problems associated with this type of study was in the area of gathering and presenting a large volume of data in a systematic manner. Table 2 has presented the types of data available and their sources used in this study. Most of these sources will continue to be available. The most useful and complete surface observations near the coast were for Point Mugu, Monterey, Pillar Point and Bodega Bay. The surface observations taken at these sites not only gave the observation at the site itself, but also comments as to whether or not fog or stratus was observed over the adjoining offshore area.

The visibility and cloudiness graphs have been pointed to as an excellent method for displaying observed conditions at the coastal sites. They give excellent continuity of what actually has been observed over large numbers of days.

The graphs used in this study were plotted by hand and, to say the least, are time-consuming to make. If a computer plotting routine was developed for this type of display, easy analysis of observed conditions could be made for large sample periods.

Oceanographic data giving visibility, sea-surface temperature, dew-point, wind speed and direction, and upper air soundings offshore is needed for an entire fog/stratus development period. It is recognized that cost and scheduling of ship time will be a primary drawback in this type of study. Coastal ship reports were looked at in the course of this study. They were too sporadically spaced in time and distance to be used for much more than general wind speed and direction, and to give a general feel of what the conditions in the area were.

The possible use of an unmanned buoy system giving sea surface temperature, surface air temperature, and dew-point should be considered. If placed offshore an area where surface observations are taken, it would be a valuable asset in determining the relationships of conditions in Stages I and II of the development model.

In this study vertical air soundings were used from coastal sites. A good correspondence was observed between the Oakland and Monterey air mass characteristics. A study in how these soundings relate to sounding at sea in the same area is needed. Some method such as that being tested by T. Calhoun and J. Norton at the Naval Postgraduate School should be considered.

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